Summer 1977

Volcanology and Geochemistry of the South Flank of Mount Baker, Cascade Range, Washington

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VOLCANOLOGY AND GEOCHEMISTRY OF THE SOUTH FLANK OF MOUNT BAKER, CASCADE RANGE, WASHINGTON

A Thesis

Presented To

The Faculty of

Western Washington State College

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science

by

Douglas McKeever

July, 1977

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Dean of Graduate School

ADVISORY COMMITTEE

Chairperson

MASTER'S THESIS

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CONTENTS

CONTENTS CONTD.

LIST OF FIGURES

LIST OF FIGURES (CONTD.)

LIST OF TABLES

PLATE

Acknowledgments

The author thanks Dr. Don J. Easterbrook, chairman of the advisory committee, for his suggestion of the thesis topic, for invaluable guidance and encouragement before and during the research, and for critically reading the manuscript. Sincere appreciation is extended to Dr. Randall S. Babcock and to Dr. David R. Pevear for their assistance and advice during various stages of the work and for critically reading the manuscript. The author thanks Dr. E.H. Brown for his assistance and particularly for encouraging the initiation of work on a thesis topic. Deepest appreciation is extended to George Mustoe for instruction in the use of the energy-dispersive x-ray fluorescence spectrophotometer, for providing several computer programs, for many hours spent in helping process the data, and for help in the field.

Special thanks are extended to officials of Whatcom Community College and to Base Camp, Incorporated, for granting leave time during Summer and Autumn of 1976 to proceed with the work. Thanks also go to the Skagit Alpine Club for making it possible to use the Park Butte Lookout as a base for the field portion of the study. Appreciation is extended to Mitchell L. Bernardi and David G. McKeever for their assistance, and to Patricia Hamilton for typing the manuscript.

Finally, I thank my wife Audrey and my children Shannon and Scott for their unending encouragement and for patiently and cheerfully enduring various hardships and inconveniences during the course of this endeavor.

Abstract

Major element chemical analysis of 97 rocks from the south side of Mount Baker was performed by energy dispersive x-ray fluorescence. Conclusions based on chemistry are: 1) Variation diagrams based on a large number of samples show that variation is not continuous nor, in general, smooth. Rocks from two major stratigraphic positions exhibit compositional coherency within each group and are interpreted as eruptive groups which were extruded over time intervals which were short compared to the lifetime of the volcanic center. The older of the two groups is called the Park Butte phase, and the younger is the Koma Kulshan phase (rocks of which form Mount Baker volcano).

2) Individual samples can be identified as belonging to one or the other of the two phases with good accuracy. 3) Koma Kulshan volcanic rocks are well clustered, are high in silica and alkalies, and are low in total iron, magnesium, and calcium compared to Park Butte volcanic rocks. 4) The Park Butte phase can be divided into three units in the study area based largely on silica and magnesium content. The Koma Kulshan phase consists of dozens if not hundreds of individual flows in the study area. Correlation of flow remnants based on comparison of major element chemistry does not appear possible at this point because variation is almost as great within single flows as it is among flows.

5) Black Buttes volcanic rocks cluster between the Koma Kulshan and Park Butte phases. The Black Buttes rocks analyzed closely resemble the high-silica Park Butte unit. 6) Samples from Table Mountain straddle the andesite - dacite line (Irvine and Baragar, 1971) and are unusually silicic considering their relatively old age. 7) The upper Sulphur Creek flow (less than about 10,300 years old) chemically resembles the Black

Buttes phase which is much older. This is an argument against differentiation from a mafic magma. 8) Basalt is present in the Park Butte phase. 9) Baker volcanic rocks are transitional between a divergent and coherent suite (McBirney, 1968; Hopson, 1972).

Field observations show that the explosion index (percentage of fragmental material) is 5 to 10 for the Koma Kulshan and Park Butte phases on the south side of Mount Baker, and 70 or more for the Black Buttes phase. The difference in explosion index may be due in part to the rate of effusion: low for the Black Buttes eruptives, high for the Koma Kulshan and Park Butte eruptives.

Koma Kulshan and Park Butte lava flows are simple, block lava type, averaging 5 km long or less. Koma Kulshan flows are 5 to more than 50 meters thick, while Park Butte flows are more than 50 meters thick. Inclined platy jointing can be used to indicate the terminus of flows in the Koma Kulshan phase because it dips back toward the source at the flow terminus.

Intratelluric plagioclase phenocrysts and synneusis structure indicate much turbulence of the magma prior to eruption. Patchy and oscillatory zoning in plagioclase indicate turbulence in the magma chamber and a decrease in confining pressure during the rise of a water deficient magma. Relative scarcity of hydrous minerals and tephra in the Koma Kulshan and Park Butte phases may indicate low water pressure. Lack of crystal settling in the Park Butte phase is shown by uniform vertical distribution of olivine throughout the flows.

INTRODUCTION

Location

Mount Baker is a large stratovolcano in northwestern Washington located about fifty kilometers east of the city of Bellingham and about twenty-five kilometers south of the United States - Canada border (Figure 1). The area selected for this study is on the south flank of the mountain, bounded by the Deming Glacier on the west, by the Squak Glacier on the east, by the 1980 meter (6,500 foot) contour on the north, and by Park Butte, Survey Point, and Schriebers Meadow on the south (Figure 2). Because this is one of the few parts of the mountain where volcanic rocks from Mount Baker volcano and from an earlier predecessor, the Black Buttes, are known to be exposed, the area was thought to provide a good opportunity to investigate the relationships between these two eruptive phases. Samples were also collected from Dillard Point, Sulphur Creek, and Table Mountain.

Previous Work

Mount Baker has not been as extensively studied as the other volcanoes of the Cascade Range. Previous reconnaissance studies began with Smith and Calkins (1904), who observed that Mount Baker erupted onto an already rugged surface and described andesites from Wells Creek and Austin Pass. Daly (1912) suggested that eruption of Mount Baker began in the Pliocene and continued through the Pleistocene and Holocene. Coombs (1939) completed the first relatively comprehensive study of the mountain, including the general petrography, speculation on the age of the volcano, a map of the approximate limits of Baker volcanic rocks, data from chemical analysis of two andesites from the north and east flanks

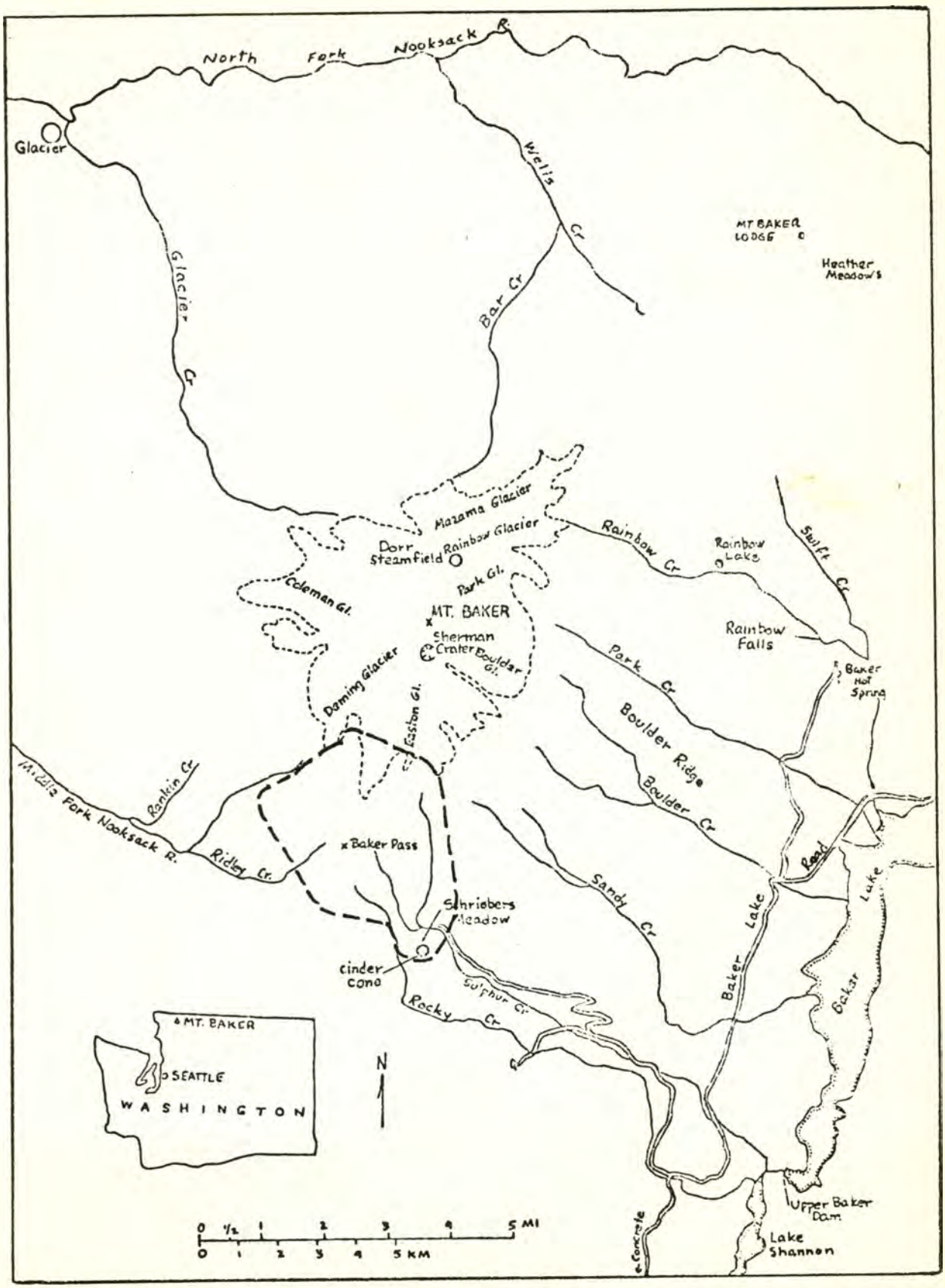


Figure 1. Location map of Mount Baker area, Washington, with the area of this study approximately located by a dashed line.

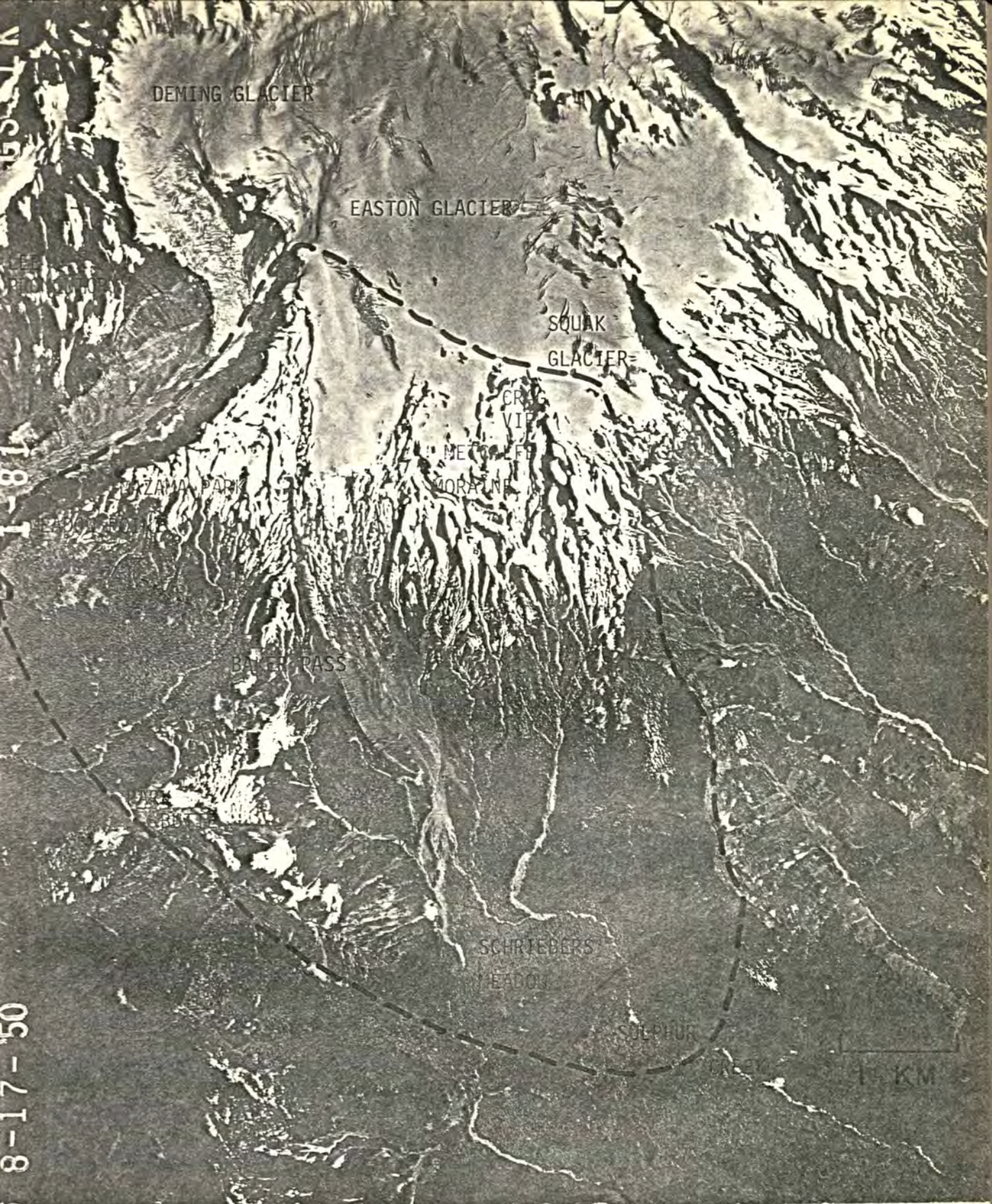


Figure 2. Aerial photograph showing boundary of study area.

of Mount Baker, and a review of various hypotheses dealing with the origin of magma that erupted from Mount Baker. Stearns and Coombs (1959) briefly described two relatively young lava flows in the lower part of Sulphur and Rocky Creeks.

Easterbrook and Rahm (1970) published two K-Ar dates of approximately 400,000 years for andesites from isolated remnants of flows on Mount Baker's flanks, and discussed Mount Baker's age and relationship to volcanism and uplift in the Cascades. Stavert (1971) analyzed twelve rocks which he thought were representative of the compositional range of the Baker volcanic rocks, including six from within the area of the present study. He also commented on the origin of the parent magma or magmas and possible trends in magmatic differentiation.

Burke (1972) reported approximate ages of about 8,700 years for two relatively young flows in the Boulder Valley during a study of the neoglaciation of that valley. Hyde and Crandell (1975, 1977 (in press)) described the origin and age of postglacial deposits and assessed the hazards from future eruptions of Mount Baker. They included a description of a number of tephra deposits, mudflows, and lava flows from within the area of the present study.

Since the initiation of increased thermal activity in Sherman Crater in March 1975, a number of studies and descriptions of the activity have been published (e.g. Easterbrook, 1975; Frank and others, 1975; Kiver, 1975; Malone and Frank, 1975; Eichelberger and others, 1976; Frank and others, 1977 (in press)).

Purpose of the Investigation

The purposes of this study are: 1) to develop a detailed strati-

graphy of eruptives on a portion of the south flank of Mount Baker; 2) to provide data on possible chemical trends in the eruptives as a function of stratigraphic position; and 3) to make a field reconnaissance of the character of lava flows in the study area, particularly in relation to stratigraphic position.

Terminology

Confusion presently exists in regard to the terminology of the Mount Baker volcanic rocks. Based on comparative degree of dissection, Mount Baker rocks have been divided into three general categories: 1) rocks of Mount Baker volcano proper; 2) rocks of the Black Buttes; and 3) scattered, isolated remnants of lava flows (Coombs, 1939). Rocks of all three categories have been referred to as "Mount Baker lavas" (Stavert, 1971). Rocks of Mount Baker volcano have been called the Mount Baker phase, and the others the Black Buttes phase (Easterbrook and Rahm, 1970; Easterbrook, 1975). In the study area rocks of Mount Baker volcano are abundant and are referred to in this report as the Koma Kulshan phase after the Indian word for Mount Baker. Rocks of the Black Buttes volcano volcano, which are scarce in the study area but are abundant across the valley of the Deming Glacier, are referred to as the Black Buttes phase. Rocks of Coombs' third group are present in the study area, but since their age relative to the Black Buttes phase is not known, it would be premature to refer to them as the "pre-Black Buttes phase." Therefore, they are called the Park Butte phase after the name of their most prominent exposure in the study area.

The term "pre-Baker" is used to refer to features older than either the Black Buttes phase or the Park Butte phase. Rocks of all three

TABLE 1. Comparative terminology of the Baker Volcanic Rocks

COMPARATIVE TERMINOLOGY

Coombs (1939)	Stavert (1971)	Easterbrook and Rahm (1970) Easterbrook (1975)	This Study[1]
Mt. Baker	Mount	Mount Baker Phase	Koma Kulshan Phase
---------		------------	-------
Black Buttes	Baker	Black Buttes Phase	Black Buttes Phase
----?----			---?---
Isolated Remnants of flows	Lavas		Park Butte Phase

1 - All volcanic rocks from the Mount Baker - Black Buttes volcanic center are collectively called the Baker Volcanic Rocks in this study.

EXPLANATION

Qa	Holocene alluvium.
Qg	Pleistocene - Holocene glacial drift, undifferentiated.
Qv	Pleistocene - Holocene volcanic rocks of Mount Baker, undivided.
Tv	Tertiary volcanic rocks, undivided.
Tg	Tertiary granitic rocks, including Lake Ann stock.
TKc	Paleocene - Cretaceous nonmarine arkose, conglomerate, siltstone, and coal of Chuckanut Formation.
Td	Tertiary peridotite of Twin Sisters.
JK	Upper Jurassic - Lower Cretaceous sedimentary and volcanic rocks of Nooksack Group.
Jv	Middle Jurassic volcanic rocks of Wells Creek.
pJph, pJgs	Pre-Upper Jurassic metamorphic rocks of Shuksan metamorphic suite. Darrington phyllite and Shuksan greenschist.
CPmv, CPm, CPms	Carboniferous and Permian sedimentary and volcanic rocks of Chilliwack Group.
pCm	Pre-Carboniferous crystalline rocks of Yellow Aster Complex.

MAP SYMBOLS

Contact. Known, approximate, and inferred are undifferentiated.

Fault. Character not designated; dashed where approximately located.

Thrust fault. Teeth on upper plate.

Map and explanation are based on Huntting and others (1961).

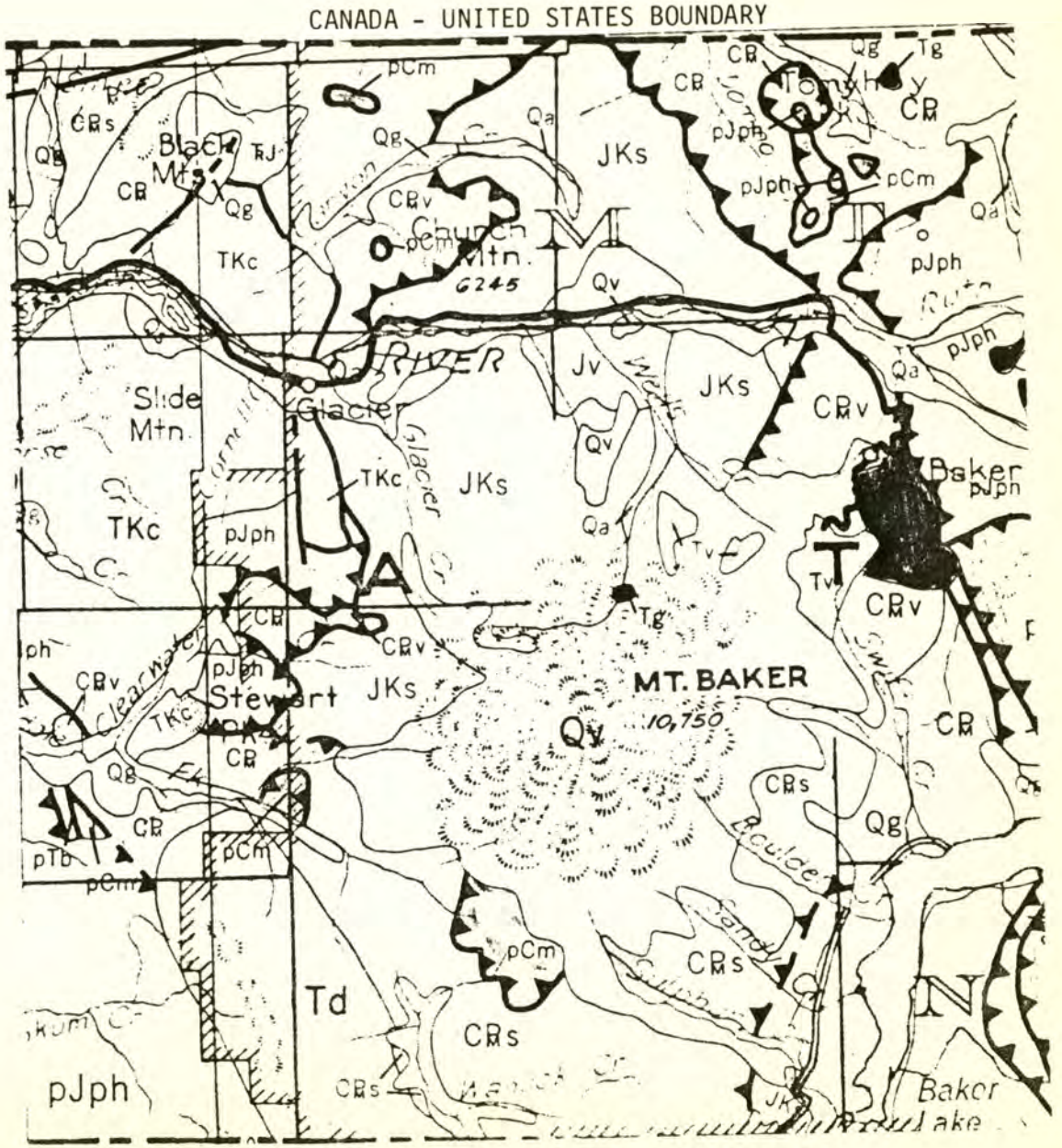


Figure 3. Generalized geologic map of the Mount Baker region.

groups will be collectively referred to as the Baker volcanic rocks. Hopefully these terms will simplify description of the rocks and their relationships. Comparative terminology is shown in Table 1.

Nomenclature of volcanic rocks discussed in this report is based on chemical and petrographic data that are listed in appropriate sections which follow.

Geologic Setting

The Baker volcanic rocks erupted over rugged topography consisting of eugeosynclinal metamorphic, sedimentary and volcanic rocks of the middle to late Paleozoic Chilliwack Group and the Upper Jurassic to Lower Cretaceous Nooksack Group (Figure 3). For a more detailed description of the bedrock geology in the vicinity of Mount Baker, the reader is referred to Coombs (1939) and Misch (1966).

Two pre-Baker rock units occur in the study area (Plate 1). Ragan (1961) identified rocks of diverse lithology, including meta-quartz diorite, hornblendite, and trondhjemitic gneiss, occurring in the vicinity of Park Butte and Loomis Mountain over an area of about 10 km^2. Misch assigned these basement rocks to the pre-Middle Devonian Yellow Aster Complex on the basis of lithology. Because of alteration, deformation, and structural location, Misch interpreted this and other occurrences of the Yellow Aster Complex on the western flank of the North Cascades to be allochthonous slices brought up from depth at the root of the mid-Cretaceous Shuksan Thrust (Misch, 1966). Rocks of the Yellow Aster Complex make up the western part of Park Butte, Survey Point and the ridge connecting Survey Point to Park Butte.

The other pre-Baker rock unit occurs in the southeastern part of the study area. Meta-volcanic rocks, slates, and phyllites of the Chilliwack

Group (Misch, 1966; Huntting and others, 1961) are exposed on the ridge between Dillard Creek and Sulphur Creek and on the northeast Cathedral Crag near Morovitz Meadows.

AGES OF THE BAKER VOLCANIC ROCKS

Introduction

Although absolute dating is beyond the scope of this study, field observations were made in the study area on the relative ages of Baker volcanic rocks.

Based on degree of dissection the Black Buttes are older than Mount Baker (Coombs, 1939). Time relationships among the eruption of the earliest Baker volcanic rocks subsequent volcanism, and the initial building and later activity of Mount Baker volcano are not well known.

Absolute Dates Outside the Study Area

Potassium - argon dates of 0.4±0.1 million years and 0.4±0.2 million years have been obtained for Baker lavas from Wells Creek and Table Mountain, respectively (Easterbrook and Rahm, 1970). These flows were considered by Coombs to be impossible to definitely correlate with either Mount Baker or the Black Buttes on the basis of evidence then available, but he felt that flow remnants such as these are at least in part contemporaneous with lavas from both early and late eruptive phases (Coombs, 1939). Easterbrook (personal communication) believes on the basis of topographic inversion that both dated flows probably pre-date the formation of Mount Baker volcano, and that they belong to an earlier episode of eruption, possibly from the Black Buttes volcano.

Topographically, both the Table Mountain and Wells Creek lavas are strongly inverted. They are at least 100 meters thick and possibly considerably thicker. Table Mountain rises 270 meters above the modern valley floor. Such strong topographic inversion shows a great deal of erosion since emplacement in ancient valleys. Thus, the Table Mountain

flows are clearly relatively old based on their topographic expression.

Relative Ages of Park Butte and Black Buttes Phases

The amount of erosion that followed the filling of a valley or covering of a slope by a lava flow indicates in a general way the relative age of the flow. By the criterion of topographic reversal the oldest exposed flows in the study area are olivine basalts and basaltic olivine andesites making up the southwest Cathedral Crag (Figure 4), the ridge north of Baker Pass, and the eastern portion of Park Butte, informally called "Tarn Plateau" in this report (Figure 5).

The base of a basaltic olivine andesite flow, called unit A for convenience, is exposed at about 1370 meters (4500 feet) near the outlet of Pocket Lake and its confluence with Rocky Creek, and on the southwestern end of southwest Cathedral Crag at an altitude of 1430 meters (4700 feet). In both locations the lava rests on rocks of the Yellow Aster Complex. A rusty-red vesicular breccia, which probably represents the top of the flow or the base of a former overlying flow, is discontinuously exposed on the tops of the remnants.

Samples which closely resemble rocks of unit A macroscopically, except for the presence of altered olivine Phenocrysts, were collected at several locations. The olivine shows altered rims in thin section. No field evidence was found of a contact separating it from unit A (samples of which were collected stratigraphically below those of the rocks presently under discussion). However, chemically the difference is marked, as shown in Table 2. Based on Table 2 at least two distinct flows or eruptive sub-groups make up the main part of the Park Butte phase. Samples from the low MgO, high Al_2O_3 group will be here called unit B.

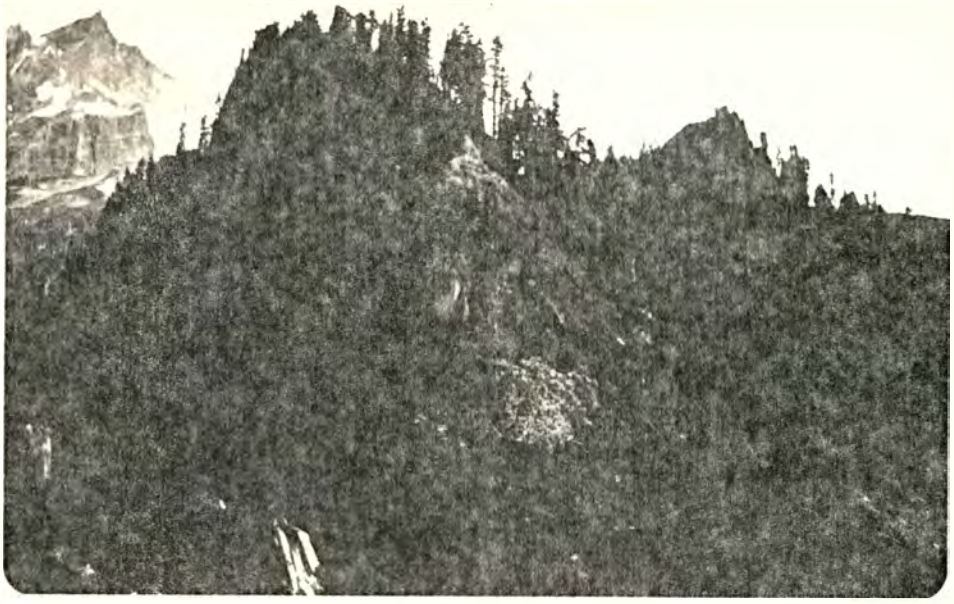


Figure 4. Cathedral Crags from the south.

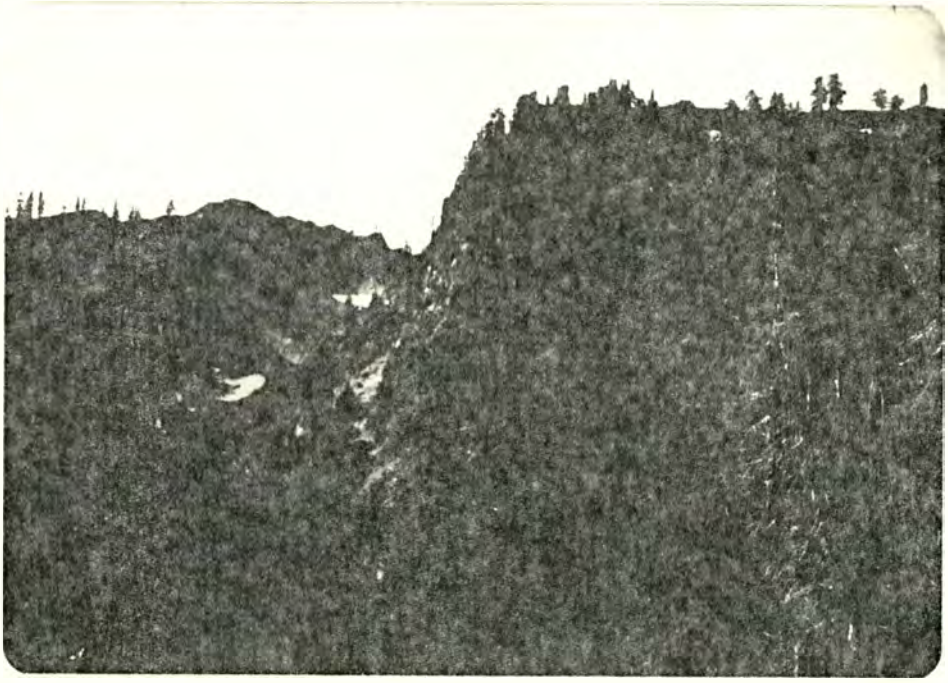


Figure 5. Eastern portion of Park Butte ("Tarn Plateau"). The height of the cliff in center is about 100 meters.

Although the modal olivine in unit A does not appear to be more abundant than in unit B, chemical differences shown in Table 2 may be due to crystal settling while a single, thick flow was cooling. Much work remains to unravel the relationship.

TABLE 2. Comparative Major Element Chemistry of Samples from Two Units of the Park Butte Phase (weight percent oxide)

	Unit A Average[1]	Unit B Average[2]
Na_2O	3.58	4.8
MgO	7.2	3.9
Al_2O_3	16.4	18.2
SiO_2	55.0	55.5
K_2O	0.87	1.05
CaO	8.7	8.26
TiO_2	0.89	0.98
Fe^{3}[2]	8.3	7.4
MnO	0.11	0.11

1 - Samples 8/5F, 8/5B, 9/9M, 8/5C, 8/6A, 8/5A

2 - Samples 9/9J, 8/5E, 8/5H, 9/9I, 7/7A

3 - Total iron expressed as Fe_2O_3

Five hundred meters east of Park Butte lookout, a remnant of an olivine basalt flow (unit C) is about 100 meters above the top of unit B adjacent to it. Unit C has a distinctive buff color where weathered. On the north unit C rests on Yellow Aster Complex rocks, but because the contact with unit B is not visible, the relative age of the two flows is not known. The two samples from unit C are 9/9K and 9/9L.

The elevations of the exposed bases of unit A and the north-south linear trend of the remnants suggests that the lava flowed in a valley

whose trend is very similar to that of the radial drainage on Mount Baker and the Black Buttes today. The implication is that the rocks of unit A, B and C came from a source in the approximate vicinity of the Black Buttes. Whether or not the flows originated from the Black Buttes volcano is not clear. They probably did not come from Mount Baker because their strongly inverted topographic position suggests they are older.

An intriguing but speculative possibility is that the basaltic olivine andesite and basalt flows originated from a volcano which have pre-dated even the Black Buttes volcano. Evidence includes: 1) the low angle of dip of the base of the flow (3-5 degrees), obtained from the elevations of the base of the flow noted earlier (this could be easily explained by ponding, however); 2) the low silica, low alkali, high ferromagnesian chemistry of the rocks, in contrast to the other rocks analyzed (see Figures 21-26 of this report); and 3) Coombs' (1939) observation of viscous flows from the Black Buttes with initial dips of as much as 30 degrees, in contrast to the apparent dip of 3-5 degrees of the olivine flows which were probably less viscous. A basaltic volcano beneath the younger volcanoes would not be without precedent in the Cascades. For example, Wise (1968, 1969) discovered olivine basalts and younger pyroxene andesites which he interpreted as remnants of a large late Pliocene volcano upon whose wreckage Mount Hood now stands. Hopkins (1976) described a basaltic shield volcano which underlies Mount Adams. Fiske and others (1963) described a Miocene shield volcano in the vicinity of Mount Rainier. The hypothesis of pre-Black Buttes volcano cannot be substantiated without reliable K-Ar dates, paleomagnetic data, and much more evidence.

Several isolated boulders in Morovitz Meadows which may be glacial erratics derived from the Black Buttes may have an alternative origin which would explain much about the relationship between the Black Buttes phase and the Park Butte phase. The boulders closely resemble both Black Buttes volcanic breccia and breccia exposed at the top of southwest Cathedral Crag. Although no chemical analyses are available for either breccia, the flows making up southwest Cathedral Crag and Tarn Plateau may merely underlie the breccias of the Black Buttes and are not significantly older than them. It is also possible that a flow analyzed by Stavert (1971) from Rankin Creek may be equivalent to the Park Buttes phase (both resemble one another petrographically as well as chemically.

Relative Age of the Koma Kulshan Phase

Although the latest tephra eruptions from Mount Baker have occurred within the last few centuries (Hyde and Crandell, 1975), including a reported eruption in 1843 (Gibbs, 1870), and increased thermal activity has been the subject of recent investigations, the ages of early eruptions that are definitely from Mount Baker volcano have not been determined.

The earliest Koma Kulshan lavas exposed in the study area are most likely the flows at the base of the 300-meter-high southeast wall of the Deming Glacier trough, between Meadow Point and Portrait Rock. This sequence of flows does not appear on the northwest side of the trough, where a considerably thicker sequence of volcanic breccias and subordinate lava flows of the Black Buttes phase is exposed in a nearly vertical section below Lee Promontory. Meadow Point and the canyon rim to the southwest consists of a thick sequence of volcanic breccia which appears

to be identical to the Black Buttes breccias across the canyon. This breccia is older than the oldest Komo Kulshan lavas exposed in the canyon wall since it stratigraphically underlies them and is separated from them by an angular unconformity. The Deming Glacier trough is thus clearly younger than the oldest Koma Kulshan lava exposed in its southeastern wall.

Although the Koma Kulshan flows in the Deming Glacier trough were not closely examined for evidence of weathering or erosion between flows, a prominent angular unconformity observed in the Squak Glacier trough shows that there was at least one interval of erosion between what may have otherwise been a rapid outpouring of a succession of lava flows in the study area during the construction of Mount Baker.

Remnants of a flow at Dillard Point are in topographic inversion and chemically are midway between Koma Kulshan and Park Butte lavas. It very closely resembles the Sulphur Creek flow chemically. In contrast to the nearly unweathered Sulphur Creek flow, the Dillard Point flow is more weathered and glacially polished. Olivine phenocrysts are more abundant in the Dillard Point lavas in any Koma Kulshan lava examined, but their low degree of alteration bears closer resemblance to Koma Kulshan than to Park Butte basaltic olivine andesites. The inverted topographic expression is evidence that the Dillard Point flow is either associated with the Park Butte phase or is a very early Koma Kulshan flow.

No continuous flows that postdate the glacial troughs of the Deming, Easton, or Squak Glaciers were found. On the contrary, all flows observed in the above valleys have been eroded by former advances of the glaciers as indicated by striations, glacial polish, and roche moutonnée. In addition, the intercanyon sloping plateaus are in places heavily mantled

with glacially-transported debris, including end moraines and lateral moraines, and exhibit the same evidence for glacial erosion that is found in the valleys.

A rusty red tephra, consisting of scoria fragments up to 2 cm in diameter, is found in exposures up to about 20 cm thick on the plateau east of the Easton Glacier. Locally the scoria is up to 2 meters thick, but those deposits are thought to have been reworked by streams. No exposures of the scoria were found above about 1525 meters (5000 feet), which is the approximate lower limit of fresh-looking morainal deposits from former extensions of the Easton-Squak Glacier.

A cinder cone about 500 meters in diameter rises about 100 meters above its base at Schriebers Meadow. The previously mentioned scoria and subsequently at least one lava flow erupted from a vent whose position is marked by the cinder cone (Easterbrook and Rahm, 1970). Pumice lying on the scoria is believed by Hyde and Crandell (1977) to be Mazama ash. In the lower part of the Sulphur Creek valley, Stearns and Coombs (1959) found two relatively young lava flows that are separated by a slightly eroded surface. The upper flow, which extends 12 km down Sulphur Creek valley, was the only flow observed at Schriebers Meadow. Exposures of the flow in the vicinity of Schriebers Meadow are limited to the Rocky Creek gorge and to several small tributaries. Evidence that the flow originated from a vent at Schriebers Meadow, rather than closer to the summit of Mount Baker, includes: 1) lack of exposures farther than 1.3 km north of the cinder cone; 2) vesicle cylinders which were observed in Rocky Creek gorge to bend at the top toward the north or northwest, which indicates a direction of flow away from the cinder cone rather than down the flank of Mount Baker; and 3) a possible slump scarp 2 to 3 meters

high and about 75 meters long located just east of Rocky Creek close to the margin of the lava flow, a feature which would be more likely to be located close to the source of lava extrusion where the lava was still relatively fluid and subsidence caused by internal drainage could occur (Finch, 1933a).

The age of the upper Sulphur Creek lava flow has been indirectly dated as younger than 10,340 ± 300 years and older than 6,600 years (Hyde and Crandell, 1975). This flow is likely the youngest exposed lava flow of the Koma Kulshan phase, with the possible exception of two andesite flows in the lower Boulder Creek valley which are younger than 8,700 (?) ± 1000 years old (Burke, 1972).

PETROGRAPHY

Introduction

This study emphasizes chemical analysis and field observations. Therefore, only twenty thin sections were viewed for the two-fold purpose of identification of textures and mineralogical relationships, and for checking chemical classification of the rocks against petrographic characteristics. Sections were prepared from rocks showing as wide a range in macroscopic features as possible. A map showing the locations of all samples is given at the end of the report (Plate 1).

General Features

The petrography of Baker lavas was described by Coombs (1939) and Stavert (1971). The Baker lavas are strongly porphyritic, containing conspicuous plagioclase phenocrysts and smaller phenocrysts of hypersthene and clinopyroxene. Microporphyritic rocks are rare, and

non-porphyritic rocks were not observed. Olivine is present in a minority of the Koma Kulshan lavas and is rarely conspicuous in hand specimens. In the Park Butte lavas, however, olivine is ubiquitous in amounts up to 5% (Figure 6). Hornblende is generally absent or insignificant but is common in a red and black flow-banded rock near the Easton Glacier. Opaque minerals are present in all the samples and occasionally are very abundant. Magnetite is the dominant opaque mineral. None of the samples contain visible quartz or alkali feldspar. Nearly all of the samples are hypocrystalline.

Hyalopilitic texture is common, and trachytic texture is seen in a few samples (Figure 7). Felty texture is rare. Cumulophyric clots displaying hypidiomorphic-granular texture are common, especially in Park Butte lavas. Clots may consist of plagioclase, clinopyroxene, hypersthene, magnetite, ± interstitial glass, ± olivine. Stavert (1971) interpreted these clots to be xenolithic gabbro or norite. Cumolophyres of 1) plagioclase, hypersthene, and magnetite; 2) of plagioclase, clinopyroxene, and magnetite; and 3) of clino- and orthopyroxene only were also observed. Plagioclase synneusis is very common (Figure 8).

Mineralogy

Plagioclase occurs in three rather distinct size ranges: 1) phenocrysts to 4 mm (average length 1-2 mm), which are actually glomerocrysts of smaller crystals in synneusis relation; 2) microphenocrysts averaging less than ½ mm in length; and 3) microlites. All three sizes are generally present, and the latter two sizes are ubiquitous. There is often striking diversity in the character of the plagioclase crystals from the same sample (Figure 8). For example, whereas zoning is the rule

Figure 6. Olivine basalt from the Park Butte phase, showing alteration to iddingsite along fractures. Sample 9/9K, 25 x.

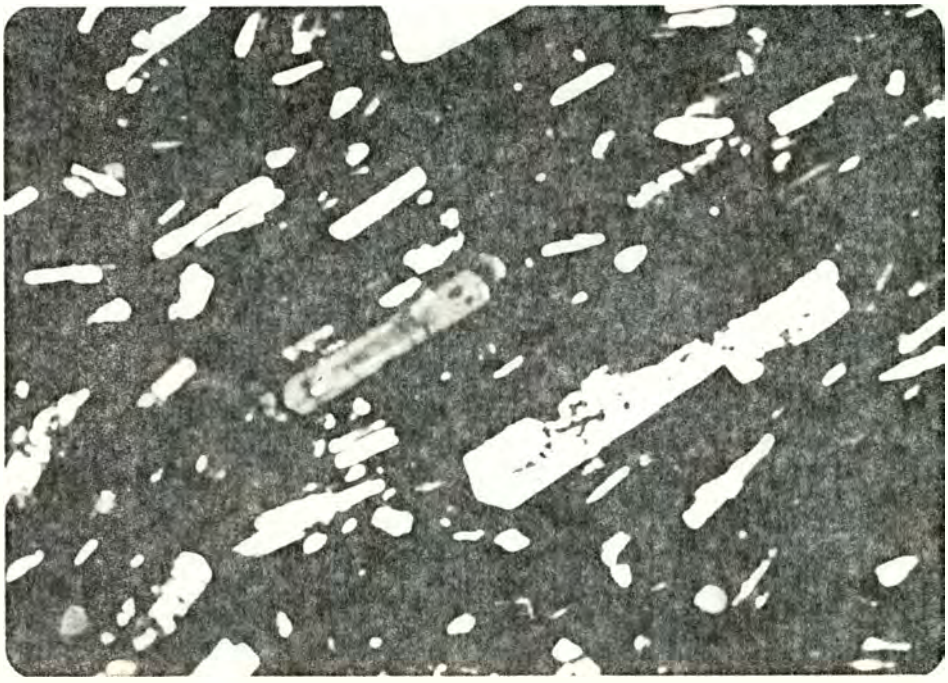


Figure 7. Trachytic texture and hornblende. Sample 9/9D, 32 x.

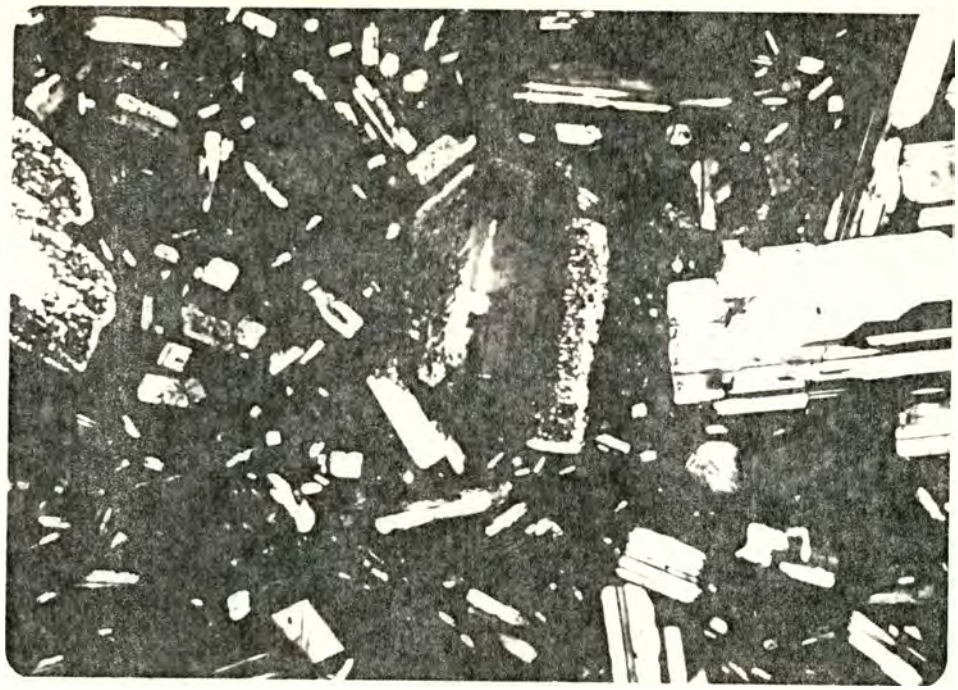


Figure 8. Synneusis and diversity of zoning in plagioclase. Sample 9/17E, 25 x.

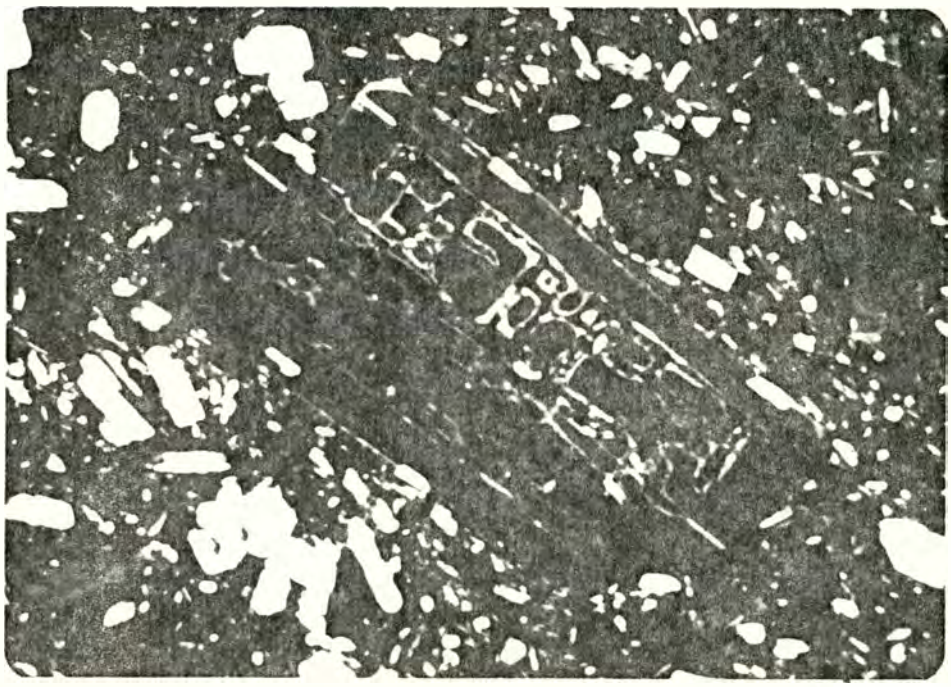


Figure 9. Patchy zoning in plagioclase. Inclusions are fine-grained magnetite and minor pyroxene. Sample 8/5H,25 x.

and often is extremely complex, adjacent crystals may be characterized by: 1) lack of zoning; 2) patchy or zoned inclusions of glass, opaques, pyroxene, or dust; 3) embayed or corroded rims; 4) fracturing; 5) continuous zoning rather than the more common oscillatory zoning; and/or 6) zoned except near the outer rim. The great variation of crystals of plagioclase within the same rock may reflect considerable turbulence and temperature variation in the magma chamber, resulting in complex and diverse single grain histories. The widespread occurrence of synneusis structure in plagioclase is thought to be strong evidence for turbulence by Vance (1969). Similar wide variations in plagiolcase have been reported from Mount Rainier (Fiske and others, 1963) and Mount Hood (Wise, 1969).

Hypersthene is the second most abundant mineral in the Baker lavas. It is usually euhedral to subhedral and crystals are usually less than 1mm in diameter. It occasionally has reaction rims of clinopyroxene, inclusions of magnetite, or is zoned. Rarely the crystals are embayed, or contain inclusions of plagiolcase microlites.

Clinopyroxene is generally less abundant than hypersthene in phenocrysts. It is usually euhedral to subhedral and is often zoned and/or twinned. Some phenocrysts contain inclusions of opaques. Clinopyroxene seems to be more abundant than orthopyroxene in the groundmass.

Olivine, where present, is generally euhedral to subhedral and is partly altered to iddingsite, mostly along grain margins or fractures (Figure 6). In some grains reaction rims of pyroxene with or without opaques are found. Zoning is rare or absent. Olivine is not limited to the chilled margins of flows, and does not even appear to be more abundant there. This contrasts with the presence of reaction rims or

resorption, which suggests that olivine was an early crystallizing phase. Olivine appears to have crystallized throughout the flows in which it is present.

Hornblende, although rarely found, often has a reaction rim of magnetite, perhaps during release of pH_2O. Hornblende was not observed as microlites and rarely as microphenocrysts, being limited to phenocrysts (Figure 7). This suggests that hornblende formed as a late intratelluric phase after which water pressure was released, inhibiting the formation of additional hornblende. Hornblende prisms are generally altered to magnetite or hematite along (001) parting, indicating resorption or denteric alteration.

Magnetite is nearly always found in the groundmass, occasionally as microphenocrysts or clots (by itself or with other minerals), and frequently as reaction rims or inclusions, particularly in pyroxenes.

Glass is present in the groundmass of most of the samples, and may be clear, pink, or pale brown. Glass is most abundant in the darker colored rocks (dark gray to black, such as at Railroad Grade), while the less glassy rocks are usually light gray to gray (Metcalfe Moraine area).

Examination of a light gray tuff breccia from near Crag View revealed that it is unwelded and contains pumice fragments as well as dark fragments consisting of microlites and microphenocrysts of plagioclase, minor microphenocrysts of pyroxene, and magnetite. Some fragments were altered to hematite. Magnetite is present both as a groundmass phase and as rare microphenocrysts in the tuff breccia. Orthopyroxene is more common than clinopyroxene as phenocrysts. Plagioclase is generally unzoned. Dust and clear glass are abundant, and irregularly-shaped, small vesicles are common.

A hand specimen of breccia from Meadow Point (Black Buttes phase) consists of angular to subrounded fragments, many of them larger than 30 cm in diameter, firmly held together by a silt to sand-sized matrix. The individual fragments are very dark gray to black, contain about 5% large irregular vesicles, and have a glass-rich groundmass with some phenocrysts of plagioclase and pyroxene. Of interest is the presence of black glass spherulites comprising about 10% of the fragments. Most of the spherulites are devitrified to a green or rusty yellow material (palagonite?). Many of the smaller, more rounded vesicles appear to be cavities formed by complete removal of the spherulites, a process which can be observed in all stages.

Crystallization History

The widespread presence of patchy zoning in plagioclase is a feature of significance in interpreting the magmatic history of the Koma Kulshan volcanics (Figure 9). In a detailed discussion of patchy zoning, Vance (1965) interpreted its presence to indicate a decrease in confining pressure on water-deficient magma during its rise in the crust. Upward displacement initiated partial resorption of intratelluric plagioclase phenocrysts and was followed by renewed crystallization at a lower pressure of more sodic plagioclase. Poikilitic inclusions, which in the Koma Kulshan lavas are pyroxene and/or magnatite, are thought by Vance to be very useful in determining paragenetic sequence since the inclusions are restricted to minerals that crystallized later than the plagioclase cores. Patchy zoning and oscillatory zoning (Figure 10) which are both very common in the Baker lavas, indicate crystallization from magmas that were unsaturated during most of the interval of consolidation, a characteristic which

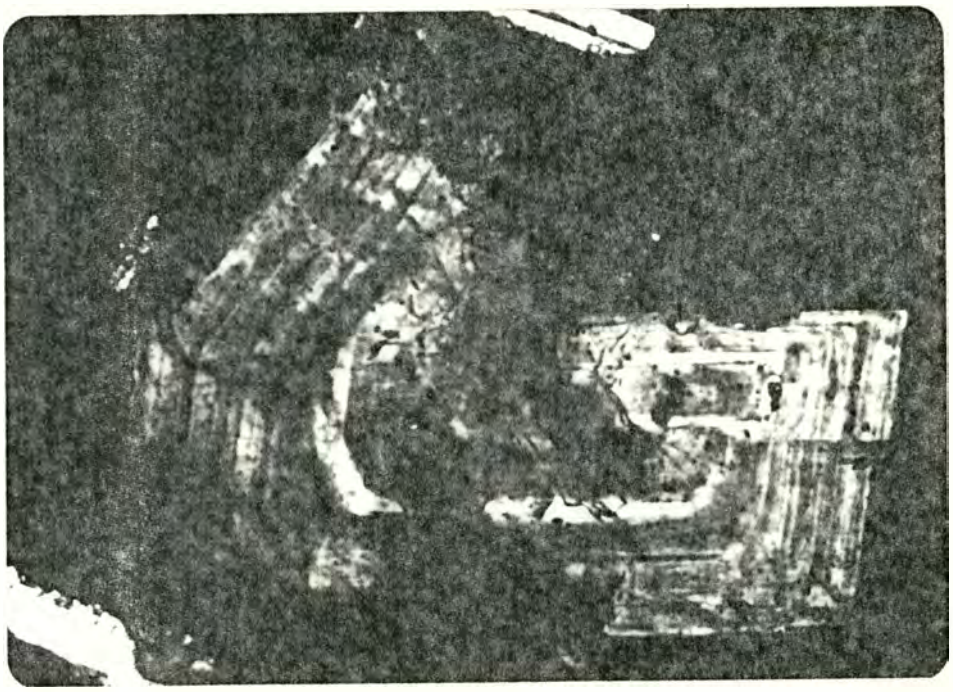


Figure 10. Oscillatory zoning in plagioclase. Sample 8/6B, 128 x.

Figure 11. Volcanic breccia of the Black Buttes phase at Meadow Point.

explains the scarcity of hornblende, even as phenocrysts.

FORM AND STRUCTURAL FEATURES

Topography and Relief

Smith and Calkins (1904) noted that Mount Baker volcano was built upon a rugged surface. Although the region was mountainous when the first eruptions began, the maximum relief at that time cannot be closely estimated. Canyon cutting undoubtedly continued throughout the growth of the Black Buttes volcano and Mount Baker. Therefore, the early relief cannot be found merely by determining the difference in elevation between the highest ridges eroded from pre-Baker rocks and the lowest valley-filling Baker volcanic rocks, because the latter may be young (such as the Sulphur Creek lava flow). Topographically inverted former valley-filling flows (e.g., Park Butte lavas, Dillard Point flow) show that deepening of valleys has occurred during late Baker time. A resonable minimum figure for the relief at the time of early eruptions is approximately 600 meters, the difference between the non-volcanic summit of Park Butte and the base of the stratigraphically earliest lava flow of the Black Buttes in the valley of the Deming Glacier.

At Mount Rainier early lavas erupted on a surface of at least 1200 meters of relief (Fiske and others, 1963) and Glacier Peak similarly was built upon mountainous terrain (Tabor and Crowder, 1969). In contrast, many if not most volcanoes in the southern Cascades were built upon relatively subdued topography, such as Saint Helens (Hyde, 1973), Hood (Wise, 1968), and Shasta (Williams, 1932).

The study area consists basically of a broad plateau, sloping

southward toward Schriebers Meadow and Mazama Park and incised by the Easton Glacier. The average slope of the surface of the plateau is about 24 degrees, which conforms to the average primary dip of the lava flows (20 ± 5 degrees). Dissection of the plateau has not been extensive, the maximum relief being only about 20 to 30 meters.

An extensive flow of the Koma Kulshan phase located southeast of Crag View is stratigraphically one of the oldest flows in the eastern part of the study area. It tops a ridge and forms a cliff up to 50 meters high and is developing into an example of inverted topography.

Form of the Lava Flows

The south flank of Mount Baker is made up of dozens, if not hundreds, of individual flows, most of which are thick, relatively narrow tongues collectively forming nearly continuous sheets of flows overlapping and interfingering with one another. This feature, coupled with incomplete exposure in many places due to removal by glacial erosion, covering by glacial deposition, and luxuriant vegetative cover at lower elevations, makes detailed mapping of the individual flows extremely difficult. Despite these difficulties, a number of field observations were made which may be useful in interpreting the history of the Baker volcanic center.

The Baker lava flows observed are of the block lava type as defined by Finch (1933b). This is not surprising, since most of the flows of orogenic regions are block lava (Macdonald, 1967). The upper surface of the Sulphur Creek lava flow commonly displays structures transitional between classic exceedingly rough aa and typical block lava, in which the fragments are markedly more regular in shape and have smoother faces

than those typical of aa.

The liquid that forms block lava flows is more viscous than the liquid that forms aa, and block lava flows are most typically andesite, although they may be basalt. The eruptions that produce block lava are likely to be considerably more explosive than those that produce aa. Macdonald (1967) suggested that the greater viscosity and explosivity is the result of lower temperature of the lava rather than lower gas content. De-emphasis of gas content is in general agreement with McBirney (1974), who claimed that the greater explosivity of andesitic lava compared to more mafic lava is not due to higher gas content in andesitic lava because there is no evidence of differences in gas content between andesite and basalt magma. This is not to say, however, that the gas pressure will be the same.

As a rule the upper surfaces of block lava flows are very uneven and are covered by "irregularly disposed hummocks and hollows" with a vertical relief of several meters (Macdonald, 1967). The advancing edge of a block lava flow may have a height of up to 6 meters, as at Paricutin (Krauskopf, 1948). The original surfaces of all the upper flows in the study area have been substantially modified by erosion and/or deposition, except for the Sulphur Creek flow. Two-dimensional exposures in cross section in the Easton, Deming, and Squak Glacier troughs reveal the irregular detail of the contacts between flows.

Several workers have discussed the difference between simple and compound lava flows, based on Nichols' (1936) definition of a flow unit as a subdivision of a single flow (e.g., Thorarinsson & Sigvaldason, 1962; Walker, 1972; Macdonald, 1972a). Macdonald (1972a) notes that compound flows (those which are divisible into flow units) are difficult

to distinguish from simple flows (those which are not so divisible) without signs of weathering between simple flows. Despite lack of noticeable signs of weathering between most flows, they are thought to be simple rather than compound because the rate of effusion of the Komo Kulshan lavas was evidently high. This reasoning is discussed more fully elsewhere in this report.

Perhaps the most widespread feature of the Baker lavas is a red breccia zone marking the top and bottom of each flow. The breccia zone at the top of one flow is often difficult to tell from the breccia zone at the base of the next higher flow, but in a few of the flows a thin weathered zone separates the two. In those cases, the upper breccia is usually thicker than the basal breccia. Planar contacts are rare and were observed only where a flow had covered a smooth flow top. The other flow contacts are highly irregular when examined in detail and are marked by complex interpenetrations that formed as moving lava filled in irregularities in the upper surface of the underlying flow. In many instances the filling was not complete, leaving highly irregular pockets and flattened cavities up to a meter long. This indicates that the basal breccia was solidified and acted as a barrier to the more fluid lava above.

The breccia consists of fragments of both porous and compact lava, generally with abundant plagioclase phenocrysts in a hypohyaline black or red matrix. Fragments range in size from clay-size and sand to boulders several decimeters in diameter. Three chemical analyses of fragments from different breccia zones show no significant differences from the central layers of the same flows.

A description of a block lava flow from Hekla volcano in Iceland revealed the movement to be essentially the same as that of slow-moving

viscous aa, except that there was a greater degree of separation into discrete plastic layers within the flow (Einarsson, 1949). The slowly advancing steep flow front rolled forward and the clinker on the top of the flow was carried forward and dumped down the flow front. The surface layer of clinker was carried passively along on the moving viscous liquid below, and the liquid, in turn, overrode the clinker that tumbled down the flow front. Indicidual portions of the flow front advanced more actively than others, both laterally and vertically. One result of this differential internal movement was the production of considerable amounts of crushed fragmental material, formed as slow movement caused the lower part of the lava to break into sharp angular blocks which were then ground up or crudely rounded by mutual abrasion. The result in the congealed flow was a structure consisting of a central massive layer formed from the pasty fluid center of the flow, with layers of fragments both above and below it.

This "tripartite" structure is seen very clearly in many of the Koma Kulshan lavas. The fragmental material of each flow is usually separated by a central massive layer of varying thickness that is generally somewhat randomly jointed. The blocks in the breccias are not a varied assemblage of different lava, such as might be torn from the walls of a conduit, but are remarkably constant in appearance and are the fragmental equivalents of the adjacent massive lava into which they grade. Many blocks have rough slaggy surfaces, most of which are reddened, but most of them are crudely rounded and are often black, especially as they grade into the massive lava. The abruptness with which the breccia zone grades into the massive zone varies, but in general it is more transitional in the lower zone than in the upper zone. Conclusions about

the behavior of the flows during eruption are necessarily conjectural because exposures at the upper elevations of the south flank of Mount Baker are buried beneath ice. However, features observed in flows at the middle elevations of the volcano reveal something of the nature of eruption.

Interpretations of the mode of origin of breccias in lava flows include breccias at Mount Rainier that grade upward into lava flows that were presumed to have been formed by steam explosions at the base of the lava as it moved down slopes mantled with mud and melting ice and snow (Fiske and others, 1963). Lava that has breccia on its top was thought to have burrowed beneath melting ice or mud. Where thin lava tongues slid downhill and mixed with large amounts of slush and meltwater, the entire flow was interpreted as having been disrupted by steam explosions and the resulting chaotic mixture continued down the slope as a mudflow, producing a laharic breccia. Where thicker flows mixed with slush and mud, irregular tongues and lenses of unshattered lava survived in the mixture.

Wise (1968) interpreted flows which overlie unbedded breccias at Mount Hood to possibly have formed when the lava flowed through large snow or ice fields. Since snow is a good insulator, extensive melting of the snow or ice was thought by Wise to be required to cause explosive fragmentation of the flow. The necessity of collecting water could explain why the flow and breccia association is found only on the flows which moved over the gentler slopes (less than 15 degrees).

Eruptions from both Mount Baker and Black Buttes volcano probably encountered snow and ice, because the mountains would support either glaciers or extensive névé slopes the year round during most, if not

all, of the Pleistocene when they were built.

Matthews (1952) attributed the widespread development of some breccias at Clinker Mountain, British Columbia, to rapid quenching in meltwater, and viewed this as evidence suggesting the proximity of ice at the time of effusion. Positive evidence of intraglacial or subglacial origin (pillows, palagonite, steam disruption) was not observed.

Form of the Tephra and Flowage Deposits

Tephra and pyroclastic flows are virtually absent in the study area. Exceptions are the volcanic breccia making up Meadow Point and the canyon rim to the southwest (Figure 11), a tuff breccia less than 5 meters thick found over an area of a few hectares southeast and east of Crag View, and the red scoria that erupted from the cinder cone in Schriebers Meadow. That the Black Buttes consist predominantly of tephra and flowage deposits has been pointed out earlier (Coombs, 1939; Easterbrook, 1975; Hyde and Crandell, 1977). Fragments of white, cream, yellow, and light red or orange-colored rock high in kaolinite, opal, and/or sulfur are found in widely scattered locations throughout the upper elevations of the study area and abundantly in stream valleys, particularly below the terminus of the Easton Glacier. While it is possible that these fragmental alteration products originated from vents or fumeroles on the south flank, it is much more likely that they originated from Sherman Crater, where similar altered material is abundant (Coombs, 1939; Bockheim and Ballard, 1975; Eichelberger and others, 1976; Frank and others, 1975; personal observation, 1976). Subsequent transport by glaciers, mudflows, or explosive eruptions would account for the distribution of this material.

Although tephra and flowage deposits associated with volcanism are apparently very scarce in the Koma Kulshan volcanic sequence except as noted above, many such deposits are possibly obscured by scree or glacial deposits at the bases of the cliffs of lava flows with which they may be interbedded. However, if such deposits are abundant, they should be visible in steep exposures of numerous lava flows such as those in the Easton and Deming Glacier troughs. This was not observed.

A sequence of diamictons is exposed in the west bank of Sulphur Creek about 20 to 50 meters south of the trail to Baker Pass. According to Hyde and Crandell (1977), the sequence consists of a mudflow more than 10,340 years old, a younger scoria, a pre-Mazama mudflow, Mazama ash (6600 years old), and a post-Mazama mudflow. Other than this, diamictons were rare in the study area. Hyde and Crandell (1977) commented on the widespread areal and vertical distribution of the post-Mazama mudflow on the divide between the Deming and Easton Glaciers, near Baker Pass, and near the saddle between southwest Cathedral Crag and Park Butte. Due to the unusually late snow cover in the summer of 1976, opportunity to observe the mudflow was restricted. It was observed only east of southwest Cathedral Crag. Hyde and Crandell suggested that the mudflow was correlative with a very large mudflow about 6,000 years old that moved at least 29 km down the Middle Fork of the Nooksack River.

A diamicton was found underlying a lava flow in the Rocky Creek valley near the outlet of Pocket Lake. The base of the diamicton is not visible, so it is not known whether it rests on another lava flow, another diamicton, or on rocks of the Yellow Aster Complex which crop out a few meters away. Boulders and cobbles in the silt-to-sand sized matrix of the diamicton are exclusively volcanic and are not well rounded. The

diamicton is poorly sorted and unstratified. The upper 1 to 1½ meters of the diamicton is stained a rusty red color and may be a baked zone. Using the criteria applied by Hyde (1973) for distinguishing diamictons, this could be (in assumed decreasing order of likelihood): till (possibly from pre-Fraser glaciation), pyroclastic flow, mudflow, or colluvium. Lack of other diagnostic characteristics and occurrence as an isolated outcrop make determination of its origin difficult.

The apparent scarcity of pyroclastic material associated with the Koma Kulshan lava suggests that explosive eruptions were small and infrequent. The explosion index, defined as the percent of fragmentary material in the total material produced (Rittman, 1962) may be as low as 5 in the study area for the Koma Kulshan phase. This compares to 80 or more for the Black Buttes phase (estimated), 85 for Mount Saint Helens (Hyde, 1973), 30 for Mount Hood (Wise, 1969), perhaps 10 for Mount Rainier (Fiske and others, 1963), and 25 or less for Mount Adams (Hopkins, 1976). The implications of the low explosion index of the Koma Kulshan phase in regard to the relatively low hazard from pyroclastic flow deposits have been noted by Hyde and Crandell (1975). However, hazards from lahars not directly associated with volcanic activity are significant.

The reason for the relative lack of pyroxlastic rocks in the Komo Kulshan volcanic sequence cannot be explained without knowledge of relative values for temperature of effusion, water content, and surface tension of the magma. As pointed out by McBirney and Murase (1970), the basic condition governing the formation of pyroclastic rocks is the relationship between the disruptive force of gas pressure in bubbles to the strength of the liquid for short-term stresses and surface tension. Surface tension controls the coalescence of bubbles because it is strongly

dependent on the composition, temperature, and water content of the magma. Evidence that the Koma Kulshan lavas had a relatively low water content is discussed in the petrography section of this report.

If percentage of fragmental material is a reliable indicator, the Black Buttes volcano erupted much more explosively than Mount Baker. This may have resulted not from higher gas content but from greater gas pressure in the upper levels of the eruptive vents (McBirney, 1974). Coombs (1939) concluded that the eruptives of the Black Buttes were apparently very viscous, based on primary dips of up to 30^{o}. Viscosity retards the expansion of gases exsolving from rising magma and results in higher pressures when magma approaches the surface (McBirney, 1974).

The observed differences in the form of the volcanic deposits in the Black Buttes and Koma Kulshan phases may be a function of rate and volume of effusion during individual eruptions. Lava of the Koma Kulshan phase averages 4-5% higher in silica than lava and pyroclastic material of the Black Buttes phase and was probably more viscous. The predominance of simple flows of the block lava type, which average several tens of meters or more thick indicates that the rate of effusion was very high (Walker, 1972). The large volume of the flows makes it less likely that they would be completely brecciated by mixing with melted snow and ice as described by Wise (1968) and by Fiske and others (1963). This mode of effusion would not rule out the formation of the tripartite structure as described by Einarsson (1949) which is so common in the Koma Kulshan lavas.

In contrast to the autobreccias in the Koma Kulshan phase, the volcanic breccias in the Black Buttes phase may not be volcanic breccias blasted from vents during volcanic explosions nor flow breccia, but

may be largely hydrovolcanic and laharic breccias. Evidence observed at Meadow Point includes the complete lack of lapilli, pumice, or ash in the matrix of the deposits and the lack of spindle-shaped bombs (see Fisher, 1960). The dominance of breccias over lava flows in the Black Buttes phase suggests that both the rate of effusion and the thickness of these presumably less viscous layers was relatively low compared to the Koma Kulshan lavas which resulted in chaotic mixing with snow and ice.

Flow Structure

Coombs (1939) noted that "a remarkable parallel streaking or flow structure, with alternating red and gray, or light and dark gray bands a fraction of an inch in thickness, is common in the Mount Baker rocks. The thinness of the bands and their perfectly straight alignment are features worthy of more study." This flow banding was seen in only about 5% of the Koma Kulshan lavas and was not observed in either the Black Buttes or Park Butte volcanic rocks. The bands are not commonly straight. Most of the banding observed resembles that shown in Figure 12. The complex swirls and inclusion patches suggest turbulent flow and relatively low viscosity. Chemical analysis of the flow shown in Figure 12 revealed an SiO_2 content of about 56%. The thickness of the bands varies from less than one cm to more than 15 cm. Often light gray bands appear to be thicker but upon closer scrutiny are shown to be broken up by thin darker gray bands. All of the banding observed was in shades of light and dark gray with the exception of red and gray banding adjacent to the terminus of the Easton Glacier. Although uncommon in the study area, the banded rocks are abundant in the few areas where they are present. Light

Figure 12. Flow structure of light and dark bands in a Koma Kulshan lava.

Figure 13. Inclined platy structure, with direction of dip indicating direction of source of the flow.

gray rock is about twice as common as dark gray in the banded rocks.

Inspection of a thin section of the red and gray banded rock shows that the black band is very rich in magnetite, whereas the red band has magnetite present but contains abundant reddish-brown glass. Hornblende is common as phenocrysts in both red and gray bands. Trachytic texture and synneusis are prominent (Figure 7).

Eichelberger and Gooley (1975) concluded on the basis of mineralogy that banded andesitic bombs at Mount Shasta formed from incomplete mixing of basaltic magma with andesite magma in the course of rapid extrusion. The relatively uniform mineralogy of the light and dark bands in the Koma Kulshan rocks does not suggest magma mixing.

Jointing

Trachytic texture is common in several of the rocks examined in thin section. In one oriented sample (8/30A), plagioclase microlites are arranged parallel to the top and presumably to the bottom of the flow, which was not exposed. Macdonald (1967) noted that marked alignment of phenocrysts or other mineral grains is a common feature in andesitic basalts and even more common in basaltic andesites. The plagioclase microlites are often so well oriented that they give the rock a definite laminated appearance. This platy structure was observed in many of the Koma Kulshan lavas in the form of platy joints. In many instances the plates are approximately parallel to the top and bottom of the flow, an observation which is in agreement with Macdonald (1967). In one exposure, a basal breccia is covered by a massive zone 1-3 meters thick, above which is a slabby zone 10-12 meters thick of exceptionally well formed sheets 2-10 cm thick, followed by an upper massive layer 4-5

meters thick. The sheets are perfectly parallel to the top and bottom of the flow.

Macdonald (1967) commented that the plates near the terminus of a flow may turn steeply upward, a fact which may be used to determine the azimuth of flow advance as well as the location of the end of the flow (assuming inclined sheeting does not occur elsewhere in the flow).

Where inclined platy structure is seen, it invariably dips back toward Mount Baker (Figure 13). Variations within the area of the presumed snout of a single flow are probably due to minor variations in the orientation of the flow planes in the lava.

Study of a block lava eruption at Hekla in Iceland revealed that individual portions of a lava front advance more actively than others, and there is a strong tendency for more or less discrete layers to push forward and slightly upward, sometimes with several layers shearing over one another (Einarsson, 1949). This type of differential movement can explain the strongly developed flow planes and the "backward" dip seen in many of the Koma Kulshan lavas.

An explanation by Wise (1968) for platy jointing found near the base of most flows at Mount Hood is similar to that of Macdonald (1967) and Einarsoon (1949). Downslope movement of the flow develops the shear planes only where solidification is nearly complete, which in most cases is near the base. Wise suggested that the piling up of lava at the bottom of a steep slope produced the platy jointing. After the front part of the flow stops, later surges of lava are thrust over it, causing curved shear zones that rise over the front part of the flow. He thought that the curved zones of platy jointing indicated that lava must have piled up in canyons or in basins on the slopes of the volcano, and that

they did not flow over or burrow under very much snow or mud.

A detailed study of the relation between fabric, jointing, and flow direction in recent Icelandic lava flows showed that jointing and plagioclase orientations are both symmetrical about flow direction (Atkinson and Stevens, 1974). Flow produces a preferred orientation of plagioclase microlites which, although weak for basalts, is strong for andesites. As cooling of the lava takes place, shrinkage may occur and primary fractures form as thermal contraction takes advantage of pre-existing microshears whose orientation is governed by the flow direction. This interpretation differs from those of Wise, Macdonald, and Einarsson in that the form and orientation of primary cooling joints may reflect the attitude of microshear planes initiated at the time of effusion rather than in late stages of movement or while cooling. The common ground is that all of the variations for the origin of platy jointing view the characteristics of the underlying slope as being important.

Coombs (1939) remarked on the "pronounced columnar jointing", but rarely are even poorly developed columns found in the study area. Well-formed columns, such as those at Wells Creek and Heather Meadows, are completely absent. Macdonald (1967) suggested that good columnar jointing in Hawaii is formed only where the underlying surface is saturated with water to bring about more effective cooling. He recommended caution be used in extending this explanation to other parts of the world, however. The absence of columnar jointing may be a result of rapid or irregular cooling, although there may be other factors involved. Waters (1960) pointed out that in the Cascades columnar jointing generally appears in olivine basalt flows over 8 meters thick and is almost ubiquitous in thick flows that have been ponded in depressions. Its absence in the

study area, particularly in the Park Butte olivine basaltic andesite, is puzzling.

Other than the platy jointing, jointing in the Baker lavas is very randomly oriented. With some imagination, one can see a joint set approximately at right angles to the flow surface, and another parallel to it. Joint blocks are often more or less equidimensional, but frequently highly irregular blocks are found. A common feature is conchoidal fracturing which produces dish-shaped blocks that are up to a meter or more across. Joint-free sections of flows are rarely found. An unusual layer of coarse-textured, unjointed rock separates the lower and upper parts of one flow which are massive and subhorizontally sheeted, respectively. Unfortunately, no samples could be obtained of the middle rock due to a complete lack of fracturing.

DIMENSIONS OF THE BAKER VOLCANIC UNITS

Introduction

McBirney (1976) has suggested that quantitative data on the volumes of volcanic rocks of various types is essential in order to choose among the many models for magma generation at convergent plate boundaries. Although he was referring to volumes on a large scale, he stressed the importance of detailed mapping, dating, correlation, and measurement on a smaller scale. However, no attempt to accurately determine the volume of volcanic rocks was made in this study because: 1) only a relatively small portion of the Baker volcanic center was studied; 2) measurements are very difficult due to covering by névé, glaciers, and vegetation; and 3) even when measurements are made with great care there

is little assurance that they are accurate because of the highly irregular underlying topography and removal of an unknown volume of material by erosion.

Methods

Field observations of the thickness of some individual flows were made, and, where possible, of the width and/or length. Flow thicknesses were determined by direct measurement or visual approximation. Length and width were estimated by locating flow boundaries on maps or on aerial photographs. Inclined platy jointing, developed only near the snout of the flow, was used to determine flow terminus. For flows originating near the summit of Mount Baker, for example, location of slabby structure indicates lengths of about 5 km. If the flows erupted from the flanks of the volcano, their lengths are less than 5 km.

An indirect method of crudely estimating the width of flows whose thickness can be determined is to use the aspect ratio - the ratio of flow thickness to flow width (Hulme, 1974). Aspect ratio depends mainly on yield stress, and for a typical intermediate composition lava may be about 0.05 (estimated from Fielder and Wilson, 1975). For a flow which is ten meters thick, the width at that point should be approximately 200 meters.

Difficulties in directly measuring meaningful thickness of flows include: 1) distinguishing between flow units of compound flows and simple flows; 2) ponding of intracanyon flows; and 3) sudden steepening of the sub-lava gradient resulting in a lava fall (Walker, 1967). The first potential difficulty is not a problem because the flows are almost exclusively simple. Falls and ponding present problems where exposures

are not extensive. However, where the Easton, Squak, and Deming Glaciers have exposed flows for long distances in their valley walls, variations of thickness of single flows are generally less than about 25% of the average thickness of the flow.

Difficulties with estimating flow width using the aspect ratio include: 1) aspect ratio is approximately independent of slope but flow depth is not, resulting in flow width being inversely proportional to slope. Changes in slope as the flow progresses will thus affect the width and depth. Depth, however, was observed to vary only slightly as previously noted. In addition, Hulme (1974) noted that lava flows generally maintain an essentially constant width for great distances. 2) Aspect ratio will vary as a result of change in effusion rate which varies with the temperature of the lava and consequently the yield stress. 3) The aspect ratio 0.05 is an interpolation from the value of 0.01 for a typical basalt and 0.125 for a typical acidic lava (Fielder and Wilson, 1975). 4) Flows confined in valleys are externally controlled in width.

Park Butte Phase

The flows making up "Tarn Plateau", southwest Cathedral Crag, and the ridge north of Baker Pass form a thick sequence. Based on uniform petrography and on concordant topographic position, these ridges appear to be remnants of a once-continuous flow at least 120 meters thick, suggesting that the flow was ponded. Single flows of andesite up to 370 meters thick at Mount Hood (Wise, 1969) have been recorded. However, as is shown in Table 2, significant chemical differences are apparent which suggest that more than one flow is present at Tarn Plateau.

The combined length of the three segments making up the Park Butte

flow is 1.9 km, but the original undissected flow was certainly longer. It has a maximum width of about 400 meters at Tarn Plateau, but is presently as little as 100 meters wide north of Baker Pass. The flow on Park Butte referred to as Flow C earlier has exposed dimensions of approximately 250 meters by 150 meters and is about 30 meters thick. It is undoubtedly a vestige of a formerly much more extensive flow.

Black Buttes Phase

Little can be said regarding the dimensions of the volcanic breccias and lava flows of the Black Buttes, inasmuch as they were not viewed other than from across the Deming Glacier trough. However, in the vicinity of Meadow Point a sequence of an undetermined number of volcanic breccia units is exposed. The combined thickness of the deposits is at least 200 meters and the upper edge of the sequence was observed to extend for more than one km southwest of Meadow Point. The observed width of the sequence was less than 100 meters. At Meadow Point the bedding of the breccias strikes N 30^{o}W and dips about 20^{o} SW. From its resemblance to the Black Buttes breccias and from its dip crudely concordant to that seen at Lee Promontory, the breccias at Meadow Point appear to be remnants of the Black Buttes volcano, isolated from the main mass due to deep erosion by the Deming Glacier.

Koma Kulshan Phase

Individual flows of the Koma Kulshan phase were observed to be from less than 5 to more than 50 meters thick, with the average being on the order of ten to twenty meters. Thinner flows are more common than thicker ones, but thicker flows are more prominently exposed and thus appear to be more common. Inasmuch as the base of the thickest flow

is not exposed, how much greater than 50 meters that flow may be is not known.

Estimates of the original length of individual flows are, at best, guesses due to incomplete exposure. An exception is the upper Sulphur Creek flow, which is 12 km long and up to 2 km wide, averaging about 1.5 km wide. The base of the flow was not observed in the study area, but it is at least 10 meters thick where exposed by the Rocky Creek gorge south of Survey Point. Observed lengths of other Koma Kulshan flow exposures average about 50 to 100 meters. One flow has a continuous exposed length of 400 meters and a discontinuous length of over 2 km. Other single flows in both the Easton and Deming Glacier troughs have discontinuous lengths of over one km. Identification of the flow segments in the field is based on similar phenocryst content and percentage, jointing, color, and stratigraphic position.

Estimates of the width of individual flows are also difficult to make. What is thought to be one flow in the Metcalfe Moraine area was measured as being more than 300 meters wide in discontinuous outcrops, but variations in chemistry within individual flows nearly as great as among different flows in that region. Therefore, little confidence can be placed in extrapolations from similar-looking but discontinuous outcrops. Extrapolation works better when estimating flow lengths because more flows are exposed in sequence in the walls of the glacial troughs radiating outward from the volcano. The maximum width which can be confidently measured is no more than 60 meters. Assuming an aspect ratio of 0.05 and a thickness of 10 meters, the width should be about 200 meters, a figure which, considering all the uncertainties inherent in this method, is in remarkable agreement with the 300 meters measured.

Discussion of Flow Behavior With Reference to Baker Eruptions

In a study of the thickness of basaltic lava flows on Mount Etna, Walker (1967) summarized the main factors which determine the thickness as follows: 1) viscosity of the flowing lava; 2) angle of the slope of the surface over which the lava is flowing; and 3) the local topography, which determines whether the lava will be ponded, form lava falls, etc. Walker suggested that the thickness of lavas of andesitic composition is governed by the same criteria, but the minimum viable dimensions would be greater than for basaltic lavas due to the greater viscosity of andesite lava.

Pinkerton and Sparks (1976) concluded that the morphology of basalt flows of the 1975 sub-terminal activity at Mount Etna was determined primarily by effusion rate. Low effusion rates resulted in compound lava fields consisting of thousands of individual flow units. Walker (1972) postulated that a relationship between simple and compound lava flows is dependent on the rate of effusion and the viscosity of the lava (Figure 14). Flows of moderate viscosity, such as andesite, can be simple even though their effusion rate is relatively low. If Walker's hypothesis is valid, then the effusion rate of some Koma Kulshan lavas which were observed to be simple in character may have been relatively low, although evidence was presented earlier which suggests that their effusion rate was often high.

The principle mechanisms causing basaltic lava flows to slow down and eventually stop were considered by Pinkerton and Sparks (1976) to be: 1) substantial reduction in effusion rate; 2) substantial increase in viscosity and yield strength of the lava in the interior of the cooling flow margins. While the necessary increase in yield strength could be

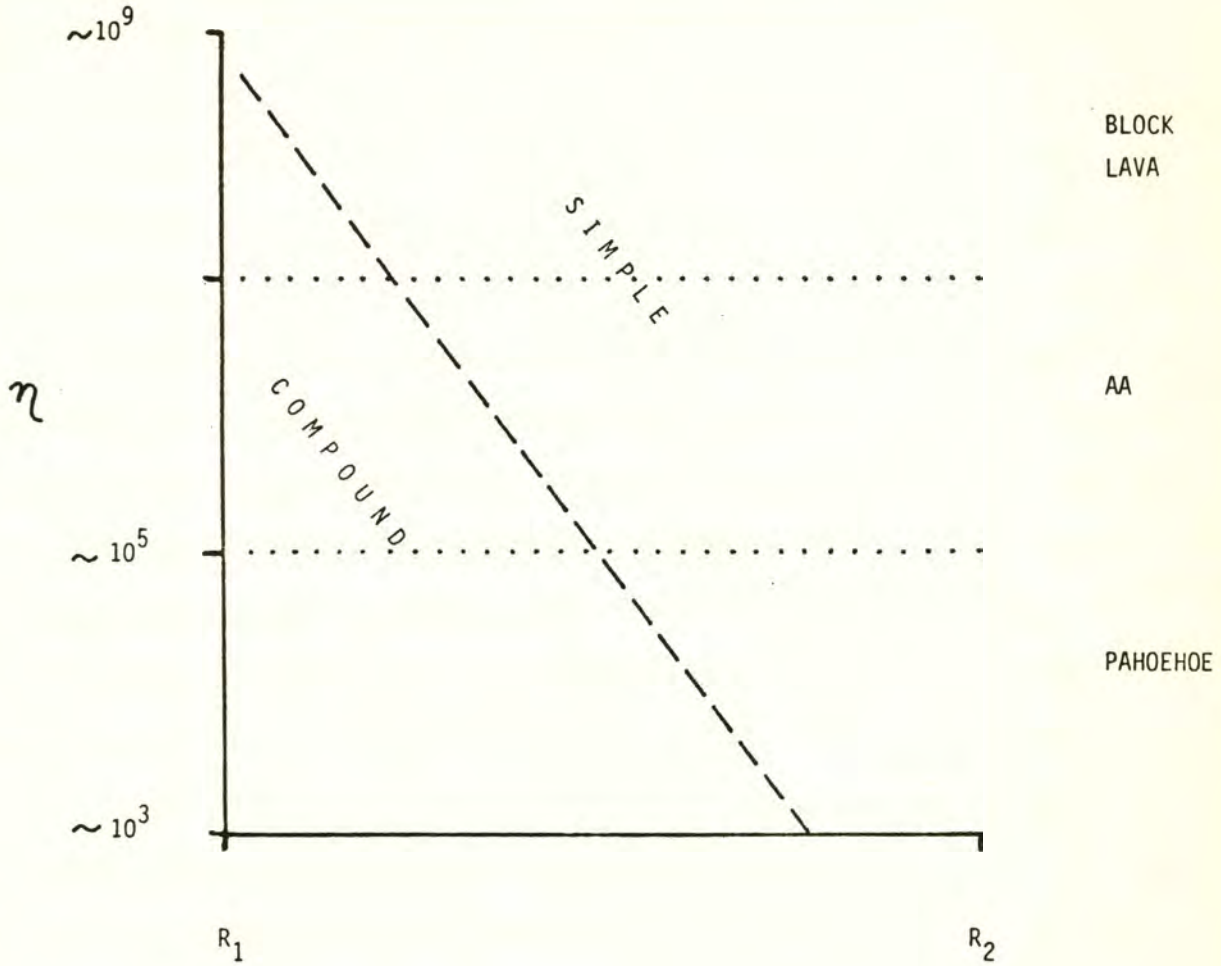


Figure 14. Postulated relationship between simple and compound lava flows as a function of rate of effusion and viscosity of the lava.

explained by cooling for the sub-terminal Etna lava (Pinkerton and Sparks, 1976), on thick flows and/or those with high effusion rates cooling has little effect on their behaviour (Hulme and Fielder, 1976). Any increase in yield strength of the interior of these lava flows has to be accounted for in terms of crystallization or volatile loss.

Hulme (1974) assumed that the final form of a flow must be determined by the physical properties of the lava, its temperature and rate of effusion, and local conditions such as topography. Flowing lava behaves as a non-Newtonian liquid (isothermal Bingham liquid) in that it commonly comes to rest on a slope as soon as the supply of fresh lava ceases and often has a high, steep flow front even though unconfined by topographic features. By matching theory with observation, Hulme argued that surface cooling of lava flows is too slow a process to be important in determining the widths and depths of lava flows. Or the principle predetermined parameters which define the shape of a flow (lava flux, slope, and lava density, plastic viscosity, and yield stress), Hulme concluded that yield stress is most important in determining flow dimensions. After flowing a short distance the flow achieves its predetermined width and depth which it maintains as long as slope and effusion rate stay constant.

Yield stress and viscosity are closely linked. Lavas of intermediate composition, such as the Baker lavas, have viscosities of roughly 10^7 poises when the flow front has stopped (Einarsson, 1949). Such a relatively high viscosity is associated with a relatively high yield stress. A lava of 56% SiO_2 has a yield stress of about 10^4 N/m^2 (Bottinga and Weill, 1972).

In general the length of a flow is limited mainly the the total amount of lava erupted in a single flow, rather than by the cooling rate.

Observations on recent flows at many locations have shown that the greater the effusion rate, the farther the lava flows (Walker, 1973).

On the basis of the preceding discussion, little can be concluded about the behaviour of the Baker lavas because little quantitative data is available concerning effusion rates, velocity of flow, pre- and post-eruption viscosity, width, or length of lava flows. Much more study of moving block lava flows is needed. Nearly all of the work in the literature deals with basaltic lava flows of either the aa or pahoehoe type for the simple reason that those are the dominant types of eruptions in the world today. In addition, basaltic eruptions are less violent than eruptions of more silicic lava and are easier to study. Volumetrically, basalt eruptions have been much more abundant than andesite eruptions in the Cascades as well (McBirney, 1976). Interpretations regarding the specific behavior of andesitic lavas need to be made cautiously if one is extrapolating from the behavior of basaltic eruptions.

CHEMICAL COMPOSITION OF BAKER VOLCANICS

Analytical Technique

The principal sampling objective was to obtain a representative suite of relatively unaltered volcanic rocks from a wide geographic area and a broad range of stratigraphic positions throughout the study area. The approximate locality of each analyzed sample is shown on Plate 1 (in pocket).

The meaning of the term "representative sample" is in need of clarification. Several workers (e.g., Kuno, 1965; Macdonald and Katsura, 1964; Watkins and Haggerty, 1967) have pointed out that if significance

is to be attached to chemical analyses of lava samples, careful selection of samples should be made, including several samples from a single flow if possible.

Primary oxidation variation is greatest toward the center of a flow. For this reason, Watkins and Haggerty (1967) suggested that at least two samples should be collected from every flow, one from near the center of the flow and the other nearer the top or bottom of the flow. This procedure was attempted, but selection of samples depended not only upon accessibility of the various portions of outcrops but also upon the convenience offered by natural fracturing. Fractures are most common at the top and bottom of the flows and, while rarely absent from the middle of a flow, are frequently so widely spaced as to make sampling very impractical. In light of this, the suite of samples collected may include a significant sampling bias from average flow composition, dependent upon vertical position within a flow. However, in cases where several samples were analyzed from different vertical positions within the same flow, whole-rock chemistry varies only slightly (generally by less than 0.1% from the mean for the samples).

Whole-rock chemical analyses were obtained for 87 new samples by x-ray fluorescence methods using an EDAX-EXAM, Model 704, energy dispersive x-ray fluorescence spectrophotometer. Weight percentages of the following oxides were obtained: Na_2O, MgO, Al_2O_3, SiO_2, K_2O, CaO, TiO_2, total iron oxide, and MnO (Table 3). In addition to the samples personally collected, ten samples collected and analyzed by Stavert (1971) were re-analyzed for comparison of analytical methods (see Appendix A). Five of Stavert's re-analyzed samples which came from the present study area are included in the graphs of chemical data. For a more complete discussion

Table 3. Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	9/9K	9/9L	8/5F	8/5D	9/9J	29-100
REFERENCE NUMBER	1	2	3	4	5	6
Na_2O	3.34	3.45	3.47	4.07	4.64	5.10
MgO	6.42	6.38	7.91	7.73	3.01	3.43
Al_2O_3	16.95	16.49	17.12	17.49	19.04	16.42
SiO_2	49.96	50.65	53.12	53.36	54.02	54.17
K_2O	0.42	0.38	0.68	0.64	0.90	1.15
CaO	8.78	9.04	8.57	9.47	8.81	6.79
TiO_2	1.00	0.96	0.92	0.85	1.05	1.30
Fe_2O_3[1]	11.35	10.89	8.53	8.36	7.19	8.60
MnO	0.16	0.16	0.12	0.12	0.11	0.14
TOTAL	98.38	99.40	100.44	102.09	98.77	97.10
qz	0.64	0.50	1.01	0.16[3]	1.92	2.27
or	2.54	2.27	3.98	3.64	5.37	7.00
ab	30.73	31.35	30.84	38.24	42.10	47.16
an	30.76	31.49	28.84	24.59	28.77	19.07
mt	4.88	4.62	3.54	3.40	3.05	4.07
il	1.43	1.35	1.27	1.17	1.48	1.86
di	11.10	11.12	10.60	16.59	12.32	12.50
hy	17.92	17.30	19.93	12.21[4]	4.98	6.07
Normative Plag. (% An)	50	50	48	39	41	29
D.I.	39.91	34.12	35.83	42.04	49.39	56.43
C.I.	35.33	34.39	35.34	33.37	21.83	24.50
FeO[2]	10.22	9.81	7.68	7.53	6.48	7.75

[1]Total iron oxide expressed as Fe_2O_3.

[2]Total iron oxide expressed as FeO.

[3]Percent Ne.

[4]Percent Ol.

Table 3 (contd.). Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	8/5B	8/11A	8/5E	8/5H	8/4A	9/9M
REFERENCE NUMBER	7	8	9	10	11	12
Na_2O	3.34	4.07	5.59	5.72	5.03	3.61
MgO	7.78	1.74	3.18	3.44	3.76	6.71
Al_2O_3	16.46	17.58	20.01	18.94	16.49	16.42
SiO_2	54.40	54.40	54.89	55.02	55.16	55.30
K_2O	0.79	0.96	0.91	0.96	1.31	0.91
CaO	9.43	7.77	9.12	8.83	6.73	9.19
TiO_2	0.92	1.04	1.01	1.14	1.33	0.86
Fe_2O_3[1]	8.65	7.83	6.94	7.31	8.90	8.31
MnO	0.12	0.12	0.10	0.11	0.14	0.12
TOTAL	101.89	95.51	101.75	101.47	98.85	101.43
qz	2.07	8.50	2.34[3]	2.56[3]	2.14	3.13
or	4.57	6.01	5.23	5.53	7.83	5.29
ab	29.36	38.71	44.90	45.81	45.72	31.91
an	27.01	28.46	26.08	22.60	18.78	25.51
mt	3.55	3.48	2.83	2.99	3.78	3.43
il	1.25	1.53	1.37	1.55	1.88	1.18
di	15.03	9.90	14.33	16.10	12.02	15.50
hy	17.15	3.42	2.93[4]	2.85[4]	7.86	14.05
Normative Plag. (% An)	48	42	37	33	29	44
D.I.	36.00	53.22	52.47	53.90	55.69	40.30
C.I.	36.98	18.33	21.46	23.49	25.54	34.16
FeO[2]	7.79	7.05	6.25	6.58	8.02	7.49

[1] Total iron oxide expressed as Fe_2O_3.

[2] Total iron oxide expressed as FeO.

[3] Percent Ne.

[4] Percent Ol.

Table 3 (contd.). Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	29-51	8/5C	29-84	7/6A	8/5A	9/9N
REFERENCE NUMBER	13	14	15	16	17	18
Na_2O	4.89	3.35	3.88	5.32	3.64	3.70
MgO	4.72	7.44	7.86	3.64	7.41	7.08
Al_2O_3	17.74	16.14	15.84	17.30	16.12	16.32
SiO_2	55.33	55.40	55.42	55.43	55.48	55.52
K_2O	0.83	0.82	0.88	1.21	0.90	0.91
CaO	8.07	9.11	9.30	7.51	8.70	9.20
TiO_2	0.94	0.92	0.92	1.24	0.95	0.85
Fe_2O_3 [1]	8.07	8.25	7.97	8.42	8.58	8.39
MnO	0.12	0.12	0.14	0.14	0.13	0.12
TOTAL	100.81	101.55	102.21	100.21	101.91	102.09
qz	0.97	3.92	1.19	0.37	2.84	2.42
or	5.42	4.76	5.05	7.11	5.20	5.25
ab	43.30	29.57	33.82	47.51	31.98	32.44
an	23.39	26.14	22.53	19.65	24.45	24.65
mt	3.66	3.40	3.56	3.51	3.52	3.43
il	1.29	1.26	1.24	1.72	1.29	1.16
di	12.88	14.64	17.81	13.93	14.23	15.94
hy	9.09	16.31	14.80	6.19	16.48	14.71
Normative Plag. (% An)	35	47	40	29	43	43
D.I.	49.69	38.25	40.06	54.99	40.02	40.11
C.I.	26.92	35.61	37.41	25.35	35.52	35.24
FeO [2]	7.27	7.43	7.18	7.58	7.23	7.56

[1] Total iron oxide expressed as Fe_2O_3.

[2] Total iron oxide expressed as FeO.

Table 3 (contd). Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	29-88	7/6D	8/30D	9/3A	8/6A	9/9B
REFERENCE NUMBER	19	20	21	22	23	24
Na_2O	4.80	5.79	3.11	4.34	4.17	3.78
MgO	3.84	3.57	1.83	2.52	6.13	4.00
Al	16.01	17.06	18.01	17.42	16.06	16.07
SiO_2	55.56	55.71	55.74	56.15	56.18	56.34
K_2O	1.17	1.27	1.17	1.32	1.12	1.23
CaO	7.01	6.98	6.02	6.85	7.21	7.02
TiO_2	1.03	1.29	0.96	0.87	0.86	0.79
Fe_2O_3[1]	7.86	8.31	6.75	6.37	7.72	7.00
MnO	0.13	0.15	0.11	0.10	0.11	0.13
TOTAL	97.41	100.13	93.70	95.94	99.56	96.36
qz	4.32	2.5[3]	16.22	7.93	3.99	9.19
or	7.09	7.44	7.50	8.14	6.61	7.57
ab	44.20	51.58	30.28	40.68	37.42	35.36
an	19.17	16.68	32.39	25.22	21.78	24.22
mt	3.71	3 46	3.07	2.79	3.23	3.06
il	1.47	1.78	1.45	1.27	1.20	1.15
di	13.21	14.14	.81[4]	8.21	11.17	9.65
hy	6.84	2.41	8.29	5.76	14.60	9.80
Normative Plag. (% An)	30	24	52	38	37	41
D.I.	55.61	59.02	54.81	56.75	48.02	52.12
C.I.	25.23	24.29	12.81	18.14	30.20	23.66
FeO[2]	7.08	7.49	6.08	5.74	6.95	6.31

[1]Total iron oxide expressed as Fe_2O_3.

[2]Total iron oxide expressed as FeO.

[3]Percent Ne.

[4]Percent Ol.

Table 3 (contd.). Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	9/9I	9/9A	7/7A	8/30A	9/16G	9/9P	29-98
REFERENCE NUMBER	25	26	27	28	29	30	31
Na_2O	4.13	3.85	4.09	5.09	4.02	4.60	5.07
MgO	3.43	2.07	3.63	2.82	2.68	2.76	4.07
Al_2O_3	16.84	17.16	16.43	17.52	16.30	16.89	16.59
SiO_2	56.48	56.85	57.08	57.45	58.26	58.35	58.42
K_2O	1.29	1.26	1.23	0.96	1.52	1.40	1.42
CaO	7.12	6.48	7.45	7.04	6.31	6.26	6.79
TiO_2	0.87	0.67	0.91	0.87	0.86	0.75	0.85
Fe_2O_3[1]	7.30	5.78	8.38	6.43	6.44	6.36	6.84
MnO	0.13	0.09	0.14	0.11	0.09	0.10	0.11
TOTAL	97.59	94.21	99.34	98.29	96.48	97.47	100.16
qz	7.66	12.59	7.81	5.89	11.79	8.92	4.59
or	7.84	7.95	7.39	5.75	9.36	8.49	8.32
ab	38.14	36.91	37.25	46.32	37.64	42.38	45.16
an	24.28	27.58	23.17	22.42	22.89	21.86	18.17
mt	3.15	2.59	3.56	2.73	2.82	2.74	3.12
il	1.25	1.00	1.29	1.23	1.25	1.07	1.17
di	9.64	5.41	11.46	10.38	7.81	8.01	12.20
hy	8.06	5.99	8.10	5.27	6.45	6.54	7.27
Normative Plag. (%An)	39	43	38	33	38	34	29
D.I.	53.64	57.45	52.43	57.96	58.79	59.79	58.07
C.I.	22.10	14.99	24.41	19.61	18.33	18.36	23.76
FeO[2]	6.58	5.21	7.55	5.79	5.80	5.73	6.16

[1]Total iron oxide expressed as Fe_2O_3.

[2]Total iron oxide expressed as FeO.

Table 3 (contd.) Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	9/2I	9/3E	9/170	9/17A	9/2B	9/2J	8/12B
REFERENCE NUMBER	32	33	34	35	36	37	38
Na_2O	5.24	4.07	4.81	4.61	4.82	4.89	4.80
MgO	3.06	3.60	3.41	3.17	4.15	3.70	3.15
Al_2O_3	16.82	16.52	16.64	16.28	16.75	16.72	16.66
SiO_2	58.55	58.64	58.67	58.71	58.75	58.80	58.86
K_2O	1.57	1.57	1.57	1.54	1.52	1.53	1.57
CaO	6.30	6.49	6.35	6.32	6.63	6.69	6.28
TiO_2	0.88	0.93	0.91	0.89	0.90	0.93	0.90
Fe_2O_3[1]	6.54	7.00	6.75	6.70	7.09	6.95	6.60
MnO	0.11	0.12	0.10	0.11	0.11	0.12	0.11
TOTAL	99.07	98.88	99.21	98.33	100.72	100.33	98.93
qz	5.14	9.91	6.74	8.42	5.35	5.70	7.43
or	9.31	9.06	9.33	9.26	8.88	8.98	9.36
ab	47.24	37.11	43.44	42.12	42.80	43.63	43.50
an	17.81	22.70	19.29	19.52	19.37	19.03	19.46
mt	2.75	2.98	2.85	2.86	2.94	2.89	2.79
il	1.23	1.32	1.27	1.26	1.24	1.29	1.27
di	10.86	8.00	9.92	9.91	10.53	11.16	9.59
hy	5.65	8.92	7.17	6.66	8.90	7.31	6.60
Normative Plag. (% An)	27	38	31	32	31	30	31
D.I.	61.69	56.08	59.51	59.80	57.03	58.31	60.29
C.I.	20.49	21.22	21.21	20.69	23.61	22.65	20.25
FeO[2]	5.89	6.31	6.08	6.04	6.39	6.26	5.94

[1]Total iron oxide expressed as Fe_2O_3.

[2]Total iron oxide expressed as FeO.

Table 3 (contd.). Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	9/3D	9/17L	9/16D	9/17M	9/9R	29-78	7/6C
REFERENCE NUMBER	39	40	41	42	43	44	45
Na_2O	4.54	4.83	4.91	4.07	4.44	5.59	5.35
MgO	3.38	3.72	2.47	3.04	3.29	1.74	3.69
Al_2O_3	16.66	16.55	16.34	16.14	16.45	16.95	16.68
SiO_2	58.91	58.92	58.93	58.97	58.99	59.01	59.02
K_2O	1.54	1.58	1.65	1.63	1.47	1.80	1.54
CaO	6.61	6.33	6.08	6.01	5.85	5.76	6.47
TiO_2	0.93	0.91	0.87	0.90	0.83	0.85	0.88
Fe_2O_3 [1]	6.92	6.85	6.08	6.81	6.90	5.91	6.72
MnO	0.13	0.11	0.10	0.12	0.12	0.09	0.11
TOTAL	99.62	99.80	97.43	97.69	98.34	97.70	100.46
qz	7.98	6.41	8.60	11.54	9.79	6.10	4.09
or	9.14	9.33	9.99	9.92	8.85	10.83	8.99
ab	40.96	43.33	45.19	37.63	40.62	51.10	47.46
an	20.63	18.80	18.12	21.58	21.01	16.13	16.75
mt	2.91	2.87	2.87	2.94	2.95	2.77	2.78
il	1.30	1.27	1.24	1.29	1.18	1.21	1.21
di	9.86	10.06	10.24	7.30	6.85	10.37	11.98
hy	7.22	7.94	3.75	7.80	8.76	1.50	6.73
Normative Plag. (% An)	33	30	29	36	34	24	26
D.I.	58.08	59.07	63.69	59.09	59.26	68.03	60.54
C.I.	21.29	22.14	18.10	19.36	19.74	15.65	22.70
FeO [2]	6.23	6.17	5.48	6.14	6.22	5.32	6.05

[1] Total iron oxide expressed as Fe_2O_3.

[2] Total iron oxide expressed as FeO.

Table 3 (contd.). Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	9/3B	9/17D	9/16C	9/2D	9/17B	7/6B	29-81
REFERENCE NUMBER	46	47	48	49	50	51	52
Na_2O	5.01	4.99	5.48	4.85	5.46	5.08	5.77
MgO	2.96	2.69	3.08	3.25	3.32	3.41	3.17
Al_2O_3	16.26	16.45	16.61	16.53	16.81	16.90	16.51
SiO_2	59.04	59.04	59.05	59.12	59.12	59.14	59.17
K_2O	1.60	1.60	1.60	1.57	1.60	1.61	1.69
CaO	6.20	6.20	6.41	6.35	6.38	6.32	6.08
TiO_2	0.90	0.86	0.89	0.92	0.91	0.92	0.94
Fe_2O_3 [1]	6.42	6.44	6.54	6.61	6.63	6.63	7.05
MnO	0.13	0.11	0.11	0.11	0.12	0.12	0.12
TOTAL	98.52	98.38	99.77	99.31	100.35	100.13	100.50
qz	7.18	7.55	4.65	7.29	4.08	5.68	3.34
or	9.57	9.59	9.41	9.32	9.35	9.46	9.86
ab	45.54	45.47	48.99	43.77	48.50	45.34	51.16
an	17.37	18.03	15.93	18.79	16.46	18.45	13.98
mt	2.72	2.74	3.00	2.79	2.75	2.76	3.20
il	1.27	1.22	1.23	1.29	1.25	1.27	1.29
di	11.02	10.55	12.59	10.30	11.89	10.18	12.65
hy	5.32	4.86	4.20	6.45	5.71	6.85	4.52
Normative Plag. (% An)	28	28	25	30	25	29	21
D.I.	62.29	62.61	63.05	60.38	61.93	60.48	64.36
C.I.	20.33	19.37	21.02	20.83	21.60	21.06	21.66
FeO [2]	5.78	5.80	5.89	5.95	5.97	5.97	6.35

[1] Total iron oxide expressed as Fe_2O_3.

[2] Total iron oxide expressed as FeO.

Table 3 (contd.). Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	9/2C	9/2K	9/16A	8/30B	9/2F	9/16J	9/3C
REFERENCE NUMBER	53	54	55	56	57	58	59
Na_2O	5.39	4.70	5.02	5.55	5.74	4.55	5.44
MgO	3.18	3.38	2.88	3.34	3.37	2.90	3.45
Al_2O_3	16.85	16.64	16.64	16.69	16.80	16.56	16.70
SiO_2	59.19	59.22	59.24	59.25	59.30	59.31	59.32
K_2O	1.60	1.53	1.66	1.45	1.58	1.59	1.56
CaO	6.40	6.51	6.17	6.38	6.31	6.37	6.56
TiO_2	0.93	0.90	0.90	0.92	0.91	0.88	0.92
Fe_2O_3 [1]	6.57	6.64	6.46	6.58	6.63	6.52	6.50
MnO	0.11	0.11	0.10	0.11	0.11	0.10	0.09
TOTAL	100.22	99.63	99.07	100.27	100.75	98.78	100.54
qz	4.66	7.74	7.05	4.31	3.06	9.30	4.23
or	9.37	9.06	9.87	8.48	9.18	9.52	9.10
ab	47.99	42.31	45.38	49.32	50.68	41.42	48.21
an	16.92	19.84	18.09	16.18	15.15	20.35	16.33
mt	2.73	2.79	2.73	2.73	2.73	2.77	2.69
il	1.28	1.26	1.26	1.27	1.25	1.24	1.27
di	11.66	10.03	10.18	12.12	12.50	9.36	12.64
hy	5.39	6.96	5.43	5.59	5.45	6.03	5.53
Normative Plag. (% An)	26	32	29	25	23	33	25
D.I.	62.02	59.11	62.30	62.11	62.92	60.24	61.54
C.I.	21.06	21.04	19.60	21.71	21.93	19.40	22.13
FeO [2]	5.92	5.98	5.82	5.93	5.97	5.87	5.86

[1] Total iron oxide expressed as Fe_2O_3.

[2] Total iron oxide expressed as FeO.

Table (contd.). Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	9/2A	8/30E	9/3F	9/9Q	9/17C	9/2G	9/2E
REFERENCE NUMBER	60	61	62	63	64	65	66
Na_2O	4.71	5.29	5.16	4.78	5.13	4.72	5.14
MgO	2.90	3.09	2.89	3.45	3.33	3.06	2.95
Al_2O_3	16.34	16.69	16.84	16.40	16.59	16.61	16.87
SiO_2	59.35	59.36	59.37	59.37	59.37	59.38	59.40
K_2O	1.66	1.63	1.61	1.39	1.56	1.61	1.64
Ca	6.11	6.37	6.23	6.00	6.47	6.24	6.33
TiO_2	0.89	0.92	0.89	0.72	0.90	0.89	0.89
Fe_2O_3[1]	6.40	6.71	6.45	6.15	6.51	6.45	6.41
MnO	0.10	0.12	0.11	0.11	0.10	0.09	0.11
TOTAL	98.46	100.18	99.55	98.37	99.96	99.05	99.74
qz	8.84	5.37	6.45	8.57	5.99	8.40	6.28
or	9.96	9.57	9.52	8.32	9.18	9.60	9.68
ab	42.95	47.20	46.37	43.48	45.87	42.76	46.09
an	18.83	16.88	18.05	19.44	17.56	19.56	18.09
mt	2.72	2.80	2.71	2.61	2.72	2.73	2.68
il	1.26	1.27	1.24	1.02	1.25	1.25	1.24
di	9.56	11.62	10.31	8.57	11.52	9.34	10.62
hy	5.87	5.29	5.36	7.99	5.91	6.36	5.32
Normative Plag. (% An)	30	26	28	31	28	31	28
D.I.	61.75	62.14	52.34	60.37	61.04	60.76	62.05
C.I.	14.41	20.89	19.62	20.19	21.40	19.68	19.86
FeO[2]	5.76	6.04	5.81	5.54	5.86	5.81	5.77

[1]Total iron oxide expressed as Fe_2O_3.

[2]Total iron oxide expressed as FeO.

Table 3 (contd.). Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	9/17J	9/17K	9/17N	9/9G	8/30C	9/9D	7/7B
REFERENCE NUMBER	67	68	69	70	71	72	73
Na_2O	4.28	5.17	5.35	3.91	5.23	4.07	5.01
MgO	2.75	3.27	3.19	2.50	2.23	2.22	2.87
Al_2O_3	16.38	16.64	16.67	15.70	16.94	16.31	16.67
SiO_2	59.43	59.45	59.45	59.64	59.65	59.71	59.72
K_2O	1.61	1.62	1.63	1.72	1.54	1.46	1.47
CaO	6.17	6.24	6.31	5.43	5.39	5.94	6.00
TiO_2	0.86	0.89	0.94	0.80	0.78	0.74	0.73
Fe_2O_3[1]	6.33	6.50	6.49	6.12	5.98	5.97	5.88
MnO	0.10	0.10	0.12	0.10	0.11	0.10	0.10
TOTAL	97.91	99.88	100.15	95.92	97.85	96.52	98.45
qz	11.26	5.99	5.19	14.68	8.83	14.23	8.36
or	9.75	9.54	9.56	10.68	9.41	9.00	8.79
ab	39.40	46.25	47.68	36.89	46.84	38.12	45.51
an	21.26	17.35	16.54	21.24	19.29	22.87	18.88
mt	2.72	2.71	2.70	2.70	2.57	2.61	2.49
il	1.23	1.24	1.30	1.17	1.12	1.08	1.03
di	8.11	10.80	11.63	5.66	6.48	6.30	8.99
hy	6.28	6.12	5.40	7.00	5.46	5.80	5.96
Normative Plag. (% An)	35	27	26	37	29	37	29
D.I.	60.41	61.78	62.43	62.25	65.08	61.35	62.66
C.I.	18.34	20.95	21.03	16.53	15.63	15.79	18.47
FeO[2]	5.70	5.86	5.85	5.51	5.38	5.38	5.30

[1]Total iron oxide expressed as Fe_2O_3.

[2]Total iron oxide expressed as FeO.

Table 3 (contd.). Chemical Analysis and Cation Norms of Baker Volcanic Rocks

SAMPLE	9/17J	9/17K	9/17N	9/9G	8/30C	9/9D	7/7B
REFERENCE NUMBER	67	68	69	70	71	72	73
Na_2O	4.28	5.17	5.35	3.91	5.23	4.07	5.01
MgO	2.75	3.27	3.19	2.50	2.23	2.22	2.87
Al_2O_3	16.38	16.64	16.67	15.70	16.94	16.31	16.67
SiO_2	59.43	59.45	59.45	59.64	59.65	59.71	59.72
K_2O	1.61	1.62	1.63	1.72	1.54	1.46	1.47
CaO	6.17	6.24	6.31	5.43	5.39	5.94	6.00
TiO_2	0.86	0.89	0.94	0.80	0.78	0.74	0.73
Fe_2O_3 [1]	6.33	6.50	6.49	6.12	5.98	5.97	5.88
MnO	0.10	0.10	0.12	0.10	0.11	0.10	0.10
TOTAL	97.91	99.88	100.15	95.92	97.85	96.52	98.45
qz	11.26	5.99	5.19	14.68	8.83	14.23	8.36
or	9.75	9.54	9.56	10.68	9.41	9.00	8.79
ab	39.40	46.25	47.68	36.89	46.84	38.12	45.51
an	21.26	17.35	16.54	21.24	19.29	22.87	18.88
mt	2.72	2.71	2.70	2.70	2.57	2.61	2.49
il	1.23	1.24	1.30	1.17	1.12	1.08	1.03
di	8.11	10.80	11.63	5.66	6.48	6.30	8.99
hy	6.28	6.12	5.40	7.00	5.46	5.80	5.96
Normative Plag. (% An)	35	27	26	37	29	37	29
D.I.	60.41	51.78	62.43	62.25	65.08	61.35	62.66
C.I.	18.34	20.95	21.03	16.53	15.63	15.79	18.47
FeO [2]	5.70	5.86	5.85	5.51	5.38	5.38	5.30

[1] Total iron oxide expressed as Fe_2O_3.

[2] Total iron oxide expressed as FeO.

Table 3 (contd.). Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	9/16I	29-85	9/9C	9/17E	8/30F	9/2H	8/12A
REFERENCE NUMBER	74	75	76	77	78	79	80
Na_2O	4.74	5.68	4.43	5.27	5.35	5.20	5.48
MgO	2.45	2.52	2.66	3.07	2.41	2.94	2.93
Al_2O_3	16.31	16.27	16.21	16.49	16.67	16.75	16.47
SiO_2	59.80	59.83	59.84	59.91	59.95	59.99	60.07
K_2O	1.78	1.92	1.56	1.66	1.73	1.71	1.76
CaO	5.70	5.35	5.67	6.17	6.10	6.10	5.88
TiO_2	0.91	0.92	0.77	0.89	0.89	0.86	0.91
Fe_2O_3 [1]	6.13	6.35	5.87	6.41	6.00	6.28	6.59
MnO	0.10	0.11	0.09	0.10	0.10	0.11	0.12
TOTAL	97.92	98.95	97.10	99.97	99.20	99.94	100.16
qz	9.98	5.65	11.99	6.30	6.82	6.66	5.67
or	10.75	11.39	9.51	9.76	10.26	10.06	10.33
ab	43.50	51.21	41.04	47.11	48.21	46.51	48.87
an	18.37	13.28	20.37	16.37	16.42	17.25	14.91
mt	2.63	2.93	2.54	2.68	2.52	2.62	2.74
il	1.30	1.29	1.11	1.23	1.24	1.19	1.26
di	8.43	10.70	6.93	11.29	11.16	10.32	11.25
hy	5.05	3.55	6.52	5.27	3.36	5.39	4.98
Normative Plag. (% An)	30	21	33	26	25	27	23
D.I.	64.23	68.25	62.54	63.17	65.29	63.23	64.87
C.I.	17.41	18.47	17.10	20.47	18.28	19.52	20.23
FeO [2]	5.52	5.72	5.29	5.77	5.40	5.66	5.94

[1] Total iron oxide expressed as Fe_2O_3.

[2] Total iron oxide expressed as FeO.

Table 3 (contd.). Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	9/16I	29-85	9/9C	9/17E	8/30F	9/2H	8/12A
REFERENCE NUMBER	74	75	76	77	78	79	80
Na_2O	4.74	5.68	4.43	5.27	5.35	5.20	5.48
MgO	2.45	2.52	2.66	3.07	2.41	2.94	2.93
Al_2O_3	16.31	16.27	16.21	16.49	16.67	16.75	16.47
SiO_2	59.80	59.83	59.84	59.91	59.95	59.99	60.07
K_2O	1.78	1.92	1.56	1.66	1.73	1.71	1.76
CaO	5.70	5.35	5.67	6.17	6.10	6.10	5.88
TiO_2	0.91	0.92	0.77	0.89	0.89	0.86	0.91
Fe_2O_3[1]	6.13	6.35	5.87	6.41	6.00	6.28	6.59
MnO	0.10	0.11	0.09	0.10	0.10	0.11	0.12
TOTAL	97.92	98.95	97.10	99.97	99.20	99.94	100.16
qz	9.98	5.65	11.99	6.30	6.82	6.66	5.67
or	10.75	11.39	9.51	9.76	10.26	10.06	10.33
ab	43.50	51.21	41.04	47.11	48.21	46.51	48.87
an	18.37	13.28	20.37	16.37	16.42	17.25	14.91
mt	2.63	2.93	2.54	2.68	2.52	2.62	2.74
il	1.30	1.29	1.11	1.23	1.24	1.19	1.26
di	8.43	10.70	6.93	11.29	11.16	10.32	11.25
hy	5.05	3.55	6.52	5.27	3.36	5.39	4.98
Normative Plag. (% An)	30	21	33	26	25	27	23
D.I.	64.23	68.25	62.54	63.17	65.29	63.23	64.87
C.I.	17.41	18.47	17.10	20.47	18.28	19.52	20.23
FeO[2]	5.52	5.72	5.29	5.77	5.40	5.66	5.94

[1]Total iron oxide expressed as Fe_2O_3.

[2]Total iron oxide expressed as FeO.

Table 3 (contd.) Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	9/17I	9/16E	9/16H	8/6D	7/23B	9/17F	9/16F
REFERENCE NUMBER	81	82	83	84	85	86	87
Na_2O	5.79	4.93	5.61	5.36	5.45	4.95	4.79
MgO	3.10	3.00	2.71	3.27	2.51	2.69	2.48
Al_2O_3	16.42	16.56	16.37	16.60	16.91	16.33	16.41
SiO_2	60.17	60.19	60.22	60.26	60.32	60.35	60.37
K_2O	1.78	1.44	1.77	1.61	1.49	1.76	1.43
CaO	5.96	6.15	5.94	5.97	5.60	5.84	6.14
TiO_2	0.88	0.75	0.91	0.76	0.76	0.86	0.74
Fe_2O_3[1]	6.36	6.24	6.47	6.07	5.81	6.17	6.11
MnO	0.10	0.10	0.11	0.10	0.10	0.10	0.10
TOTAL	100.56	99.36	100.11	100.00	98.95	99.05	98.57
qz	4.17	8.83	5.51	6.46	7.62	8.93	9.69
or	10.38	8.54	10.39	9.44	8.84	10.48	8.54
ab	51.30	44.45	50.03	47.77	49.15	44.81	42.65
an	13.38	18.89	14.16	16.36	17.36	17.28	20.17
mt	2.63	2.63	2.69	2.77	2.45	2.61	2.56
il	1.21	1.05	1.26	1.05	1.06	1.21	1.05
di	12.64	9.41	12.09	10.43	8.44	9.54	8.54
hy	4.29	6.21	3.88	5.71	5.08	5.13	6.78
Normative Plag. (% An)	21	30	22	26	26	28	32
D.I.	65.85	61.82	65.93	63.67	65.61	64.22	60.88
C.I.	20.77	10.30	19.92	19.56	17.03	18.49	18.93
FeO[2]	5.73	5.62	5.83	5.47	5.23	5.56	5.50

[1]Total iron oxide expressed as Fe_2O_3.

[2]Total iron oxide expressed as FeO.

Table 3 (contd.) Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	9/9F	9/17G	9/9H	9/17H	8/6C	9/16B	29-59
REFERENCE NUMBER	88	89	90	91	92	93	94
Na_2O	4.80	4.81	4.37	5.32	5.54	5.32	4.84
MgO	2.42	2.61	2.91	2.54	3.27	2.98	1.10
Al_2O_3	16.23	16.13	16.02	16.35	16.52	16.54	14.71
SiO_2	60.38	60.39	60.45	60.79	60.83	60.96	61.04
K_2O	1.67	1.83	1.70	1.86	1.82	1.50	2.32
CaO	5.77	5.76	5.81	5.79	5.66	6.18	3.64
TiO_2	0.76	0.91	0.79	0.86	0.80	0.72	0.73
Fe_2O_3[1]	5.93	6.23	6.26	5.89	6.08	5.98	4.81
MnO	0.09	0.10	0.10	0.10	0.10	0.10	0.10
TOTAL	98.05	98.77	98.41	99.50	100.62	100.28	93.29
qz	10.54	9.76	11.78	7.64	5.65	7.57	15.13
or	10.06	10.95	10.24	10.99	10.59	8.79	14.72
ab	43.96	43.75	39.99	47.79	49.01	47.37	46.68
an	18.17	17.24	19.45	15.25	14.62	16.68	12.42
mt	2.54	2.65	2.67	2.47	2.51	2.49	2.38
il	1.08	1.28	1.12	1.20	1.10	0.99	1.09
di	8.83	9.37	7.95	10.79	10.44	10.98	5.58
hy	4.83	5.00	6.80	3.86	6.07	5.13	2.00
Normative Plag. (% An)	29	28	33	24	23	26	21
D.I.	64.56	64.46	62.01	66.42	65.25	63.73	76.53
C.I.	17.28	17.30	18.57	18.32	20.12	19.59	11.05
FeO[2]	5.34	5.61	5.64	5.31	5.48	5.39	4.33

[1]Total iron oxide expressed as Fe_2O_3.

[2]Total iron oxide expressed as FeO.

Table 3 (contd.). Chemical Analyses and Cation Norms of Baker Volcanic Rocks

SAMPLE	9/9E	7/23A	29-65
REFERENCE NUMBER	95	96	97
Na_2O	4.36	4.91	5.45
MgO	2.42	2.34	2.05
Al_2O_3	15.79	15.84	16.15
SiO_2	61.53	61.62	61.80
K_2O	1.70	1.98	1.98
CaO	5.63	4.74	4.85
TiO_2	0.77	0.85	0.72
Fe_2O_3	5.88	5.74	5.59
MnO	0.10	0.11	0.11
TOTAL	98.18	98.13	98.70
qz	13.99	11.73	9.64
or	10.28	11.92	11.80
ab	40.06	44.92	49.36
an	18.93	15.63	13.88
mt	2.52	2.45	2.59
il	1.10	1.21	1.01
di	7.73	6.67	8.32
hy	5.39	5.47	3.39
Normative Plag. (% An)	32	26	22
D.I.	64.33	71.06	70.80
C.I.	16.74	15.80	15.31
FeO[2]	5.30	5.17	5.04

[1]Total iron oxide expressed as Fe_2O_3.

[2]Total iron oxide expressed as FeO.

of sample preparation, sources of error, precision, and accuracy, refer to Appendix A.

Presentation of Chemical Data

The reasons for graphically portraying chemical data in this report are: 1) as a means of classification and naming, and 2) as a means of portraying petrogenetic relations among rocks. Only those samples with major oxide totals of between 98.0 and 101.5% were plotted, and totals were not normalized to 100.00%.

It is well known that the Cenozoic volcanoes of the Cascade Range are subalkaline (e.g., McBirney, 1968). Coombs (1939) and Stavert (1971) placed the Baker volcanics in the calc-alkaline series, and Stavert listed pyroxene, andesite and andesite as the dominant rock types, with minor basaltic andesite (with or without olivine) and hornblende andesite. Neither Stavert nor Coombs described any basalt, dacite, or rhyolite.

In the literature, subdivisions of the calc-alkaline series are based on so many different parameters that any attempt to be consistent with previous usage must be a compromise. As variation from andesite to basalt and from andesite to dacite is continuous, there are many rocks whose proper classification is difficult to determine. What follows is based roughly on the scheme proposed by Irvine and Baragar (1971).

To confirm that the Baker volcanics belong to the calc-alkaline series, an AFM plot was made (Figure 15). As a cross-check a variation diagram of Al_2O_3 versus normative plagioclase composition was prepared (Figure 16), since calc-alkaline basalts and andesites are generally high-alumina types containing 16 to 20% Al_2O_3, whereas their tholeiitic counterparts have only 12 to 16%. Figures 15 and 16 show conclusively

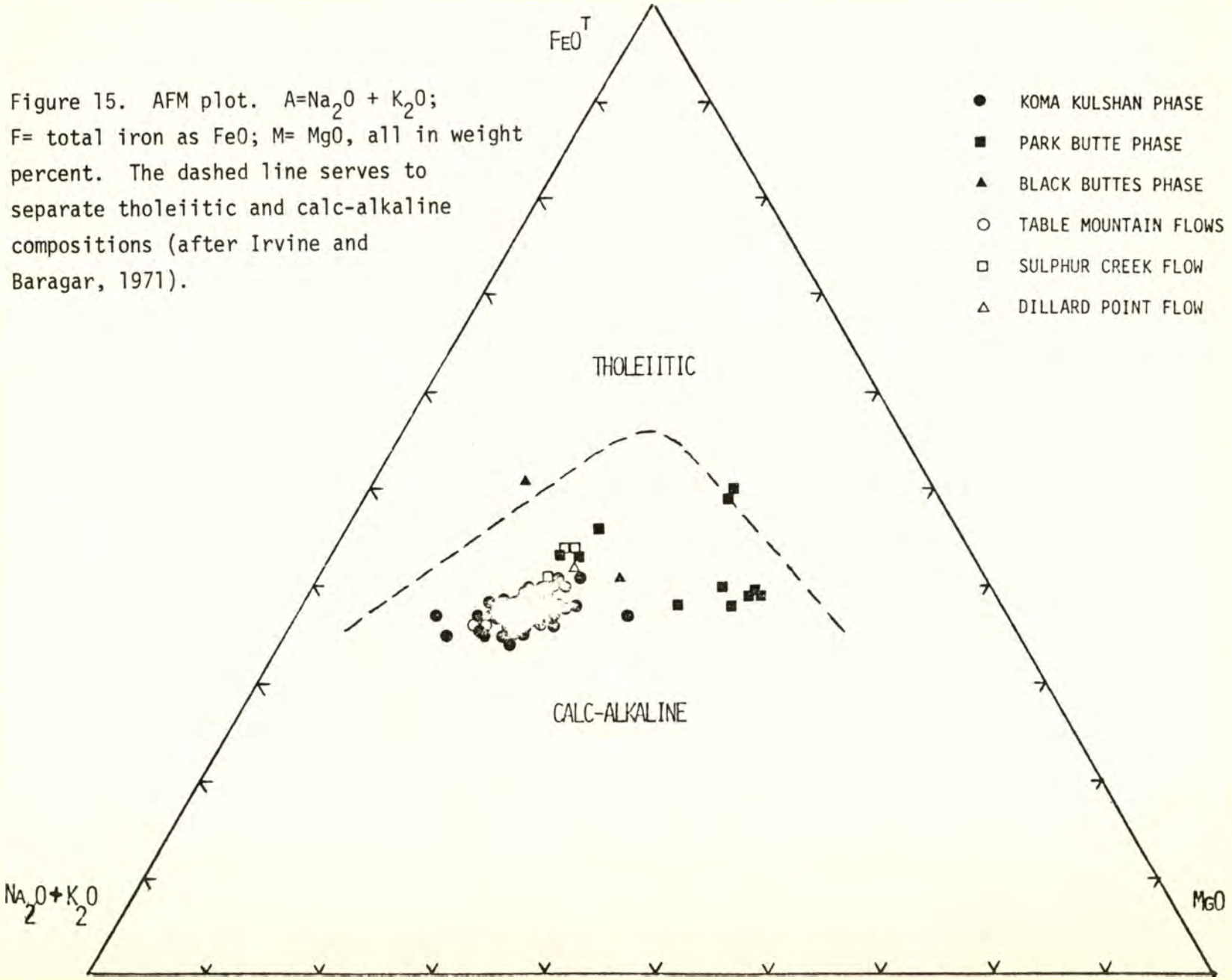


Figure 15. AFM plot. $A=Na_2O + K_2O$; F= total iron as FeO; M= MgO, all in weight percent. The dashed line serves to separate tholeiitic and calc-alkaline compositions (after Irvine and Baragar, 1971).

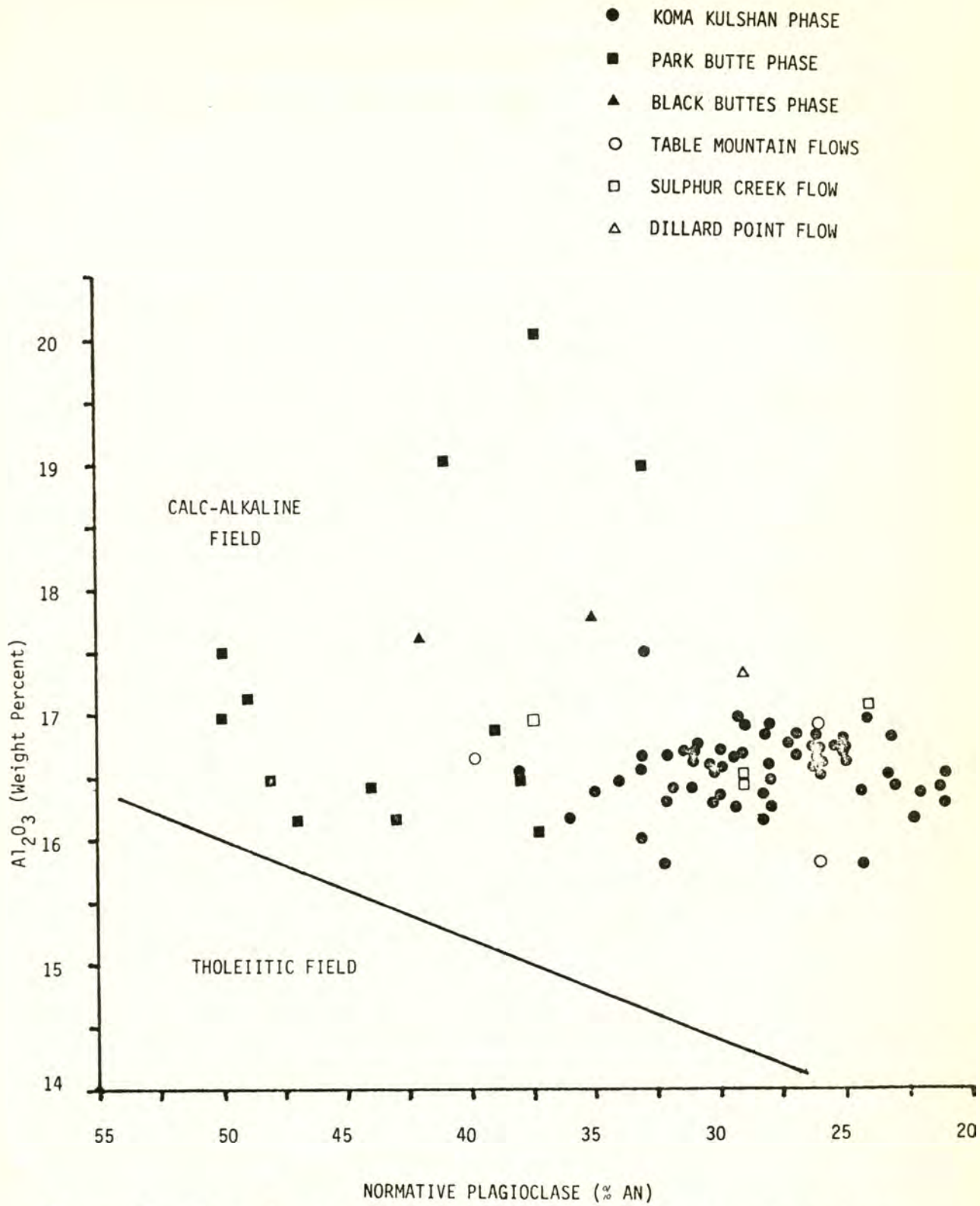


Figure 16. Plot of weight percent Al_2O_3 versus normative plagioclase composition. Dividing line between tholeiitic field and calc-alkaline field is that proposed by Irvine and Baragar (1971).

that the Baker volcanics do indeed belong the calc-alkaline series.

Figure 17 is a plot of normative color index versus normative plagioclase composition (after Irvine and Baragar, 1971). This diagram has the important feature that the two parameters on which it is based correspond fairly closely to petrographic features, but has the disadvantage that normative plagioclase composition is dependent on Na_2O and so may be sensitive to the analytical accuracy of Na determination in EDAX-EXAM analysis. Chemical data from the Cascades and Thingmuli in Iceland constitute the main control for the classification divisions in Figure 17 (Irvine and Baragar, 1971). Graphs of color index versus silica (Figure 18) and silica versus differentiation index (Figure 19) (Thornton and Tuttle, 1960) were also made. Arbitrary boundaries for the four rock types in Figures 18 and 19 are from Wise (1969).

A plot of Ab'-An-Or was made to determine classification based on potassium content, where Ab' is Ab + 1.67 Ne (Figure 20). Finally, the results were checked against appropriate comparative analyses from the literature (summarized in Irvine and Baragar, 1971), and against the rock's petrographic characteristics (using criteria suggested by Ewart (1976) and Wise (1969). Agreement among classification schemes was good.

To portray petrogenetic relations selected variation diagrams were used to summarize the chemical data for the suite of rocks. Wright (1974) recommended MgO variation diagrams be used for basaltic rocks and for some andesites, but suggested SiO_2 variation be used for most andesites. Both MgO and SiO_2 were used as the abscissa, and the results compare favorably. Only the SiO_2 variation diagrams are included in this report (Figures 21 through 26).

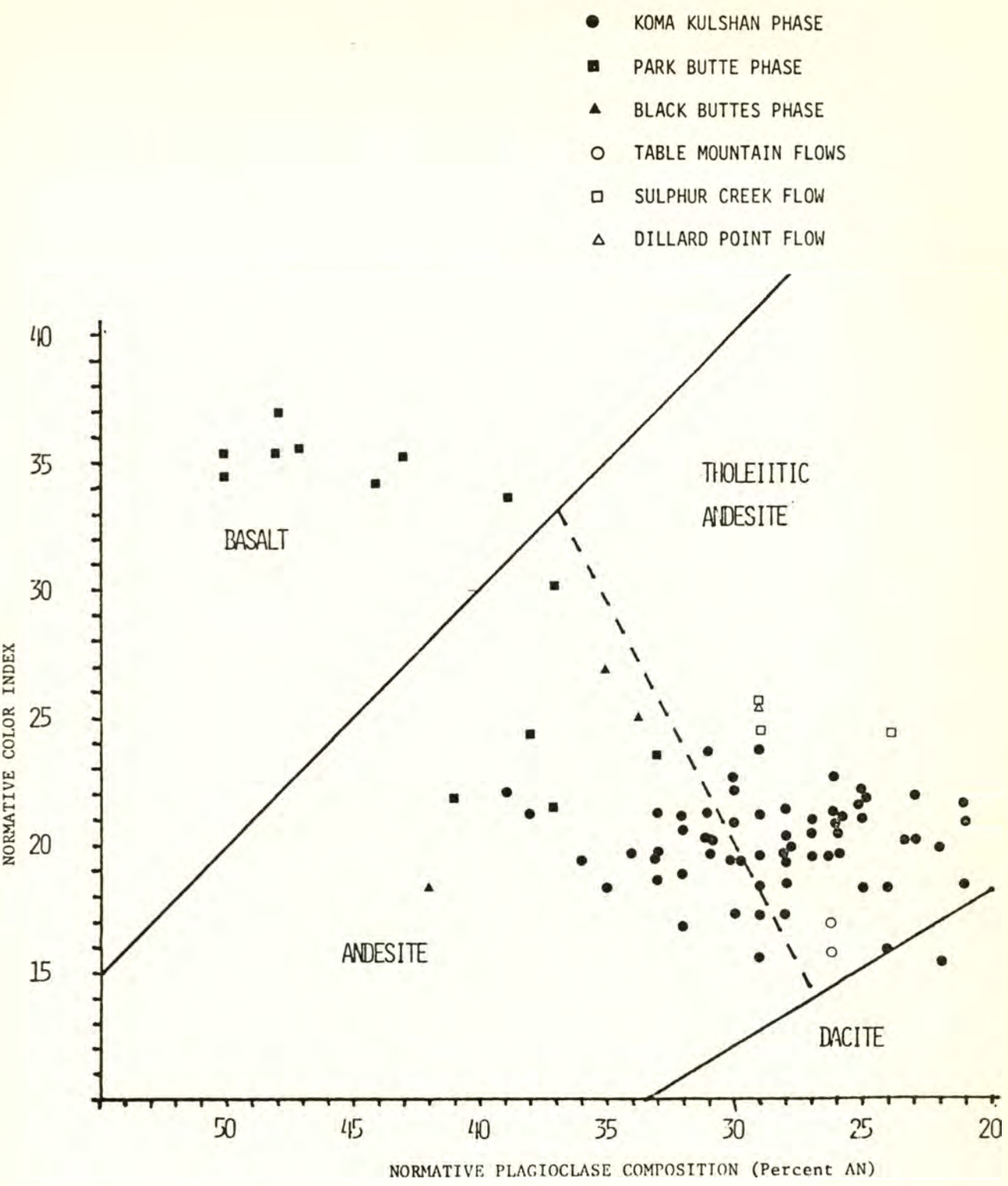
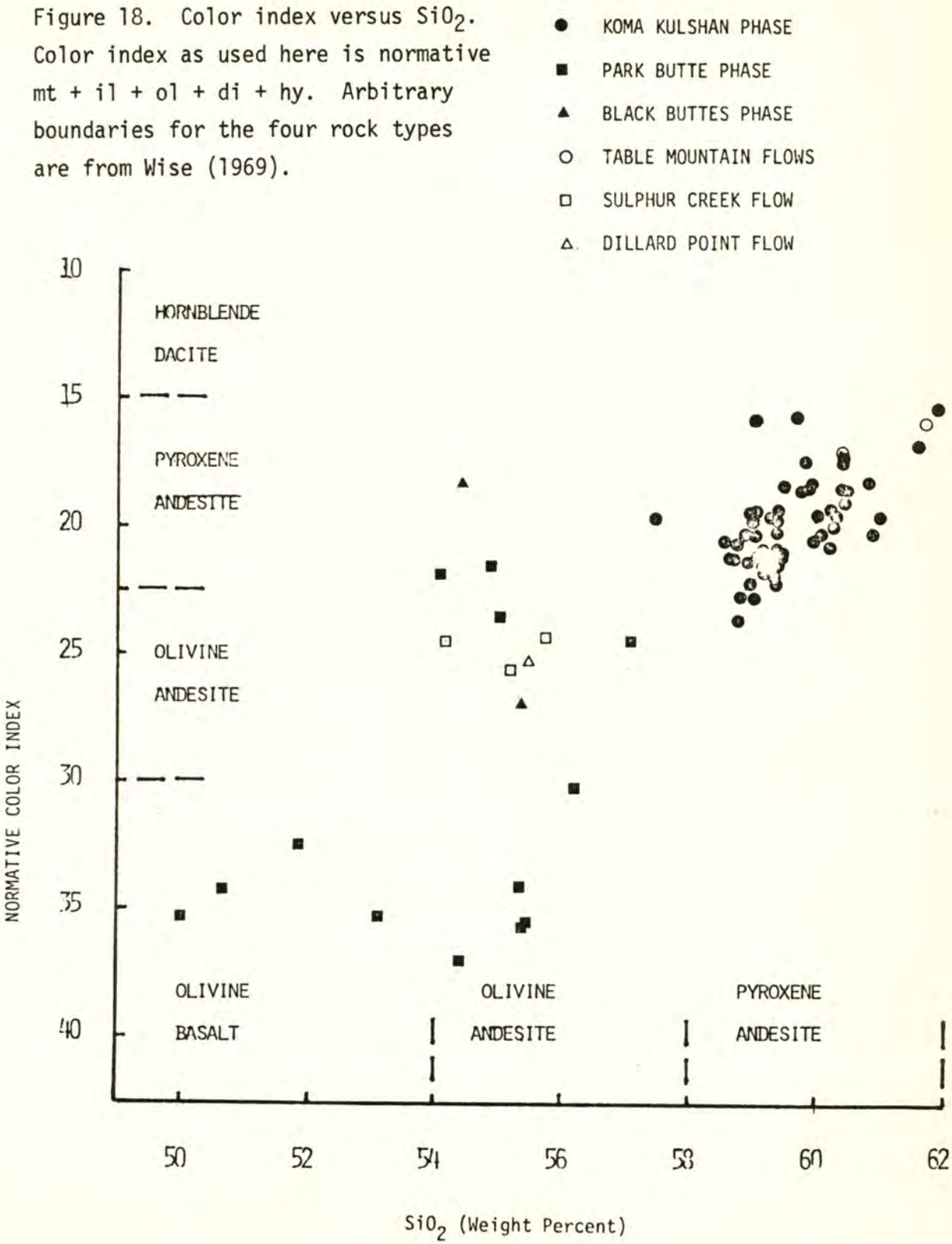


Figure 17. Plot of normative color index versus normative plagioclase composition. Dividing lines are those proposed by Irvine and Baragar (1971).

Figure 18. Color index versus SiO_2. Color index as used here is normative mt + il + ol + di + hy. Arbitrary boundaries for the four rock types are from Wise (1969).



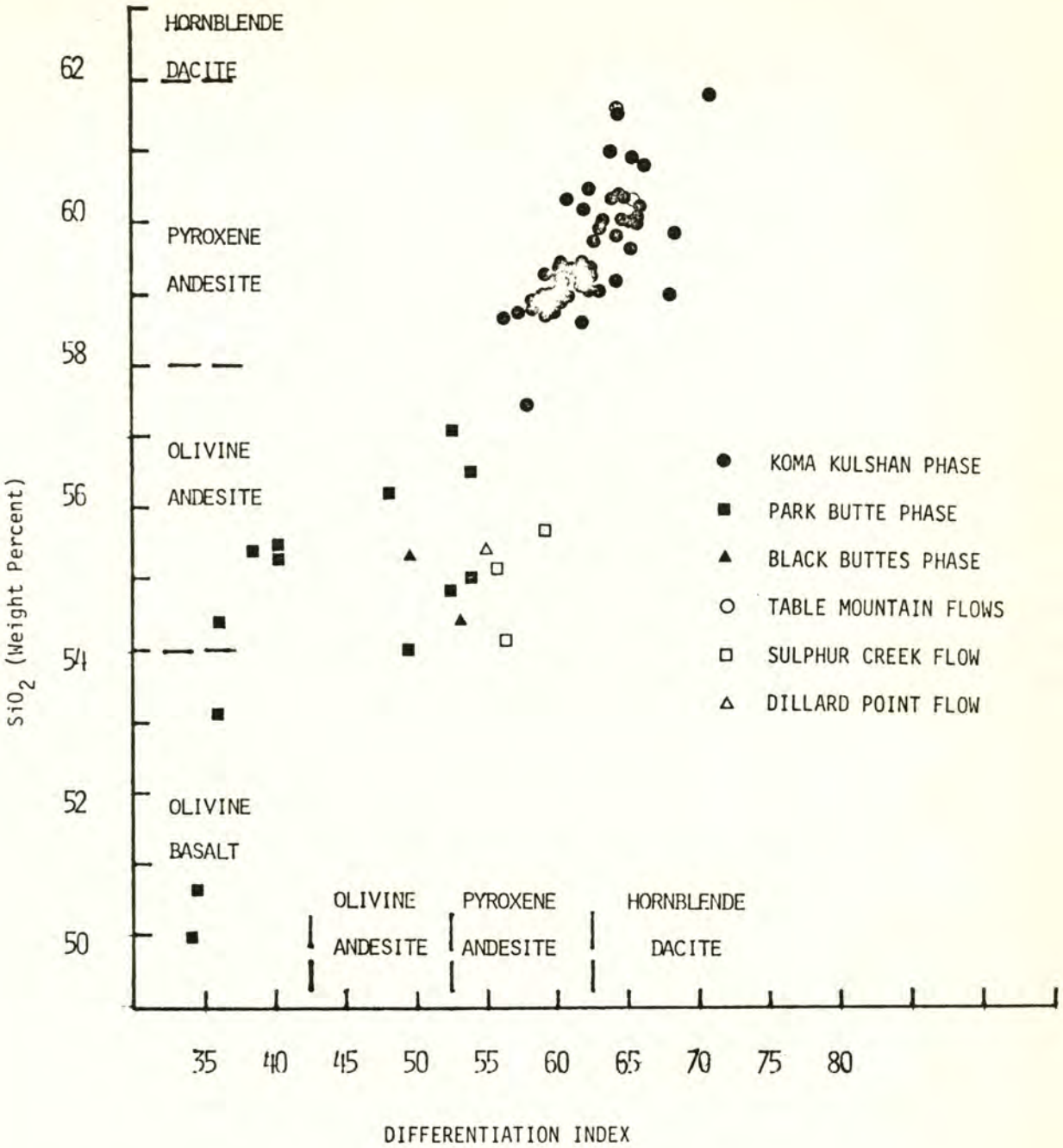


Figure 19. SiO_2 versus Differentiation Index. Approximate limits of each of four rock types are shown along the axes (after Wise, 1969). Differentiation Index (Thornton and Tuttle, 1960) = normative qz + ab + or + ne.

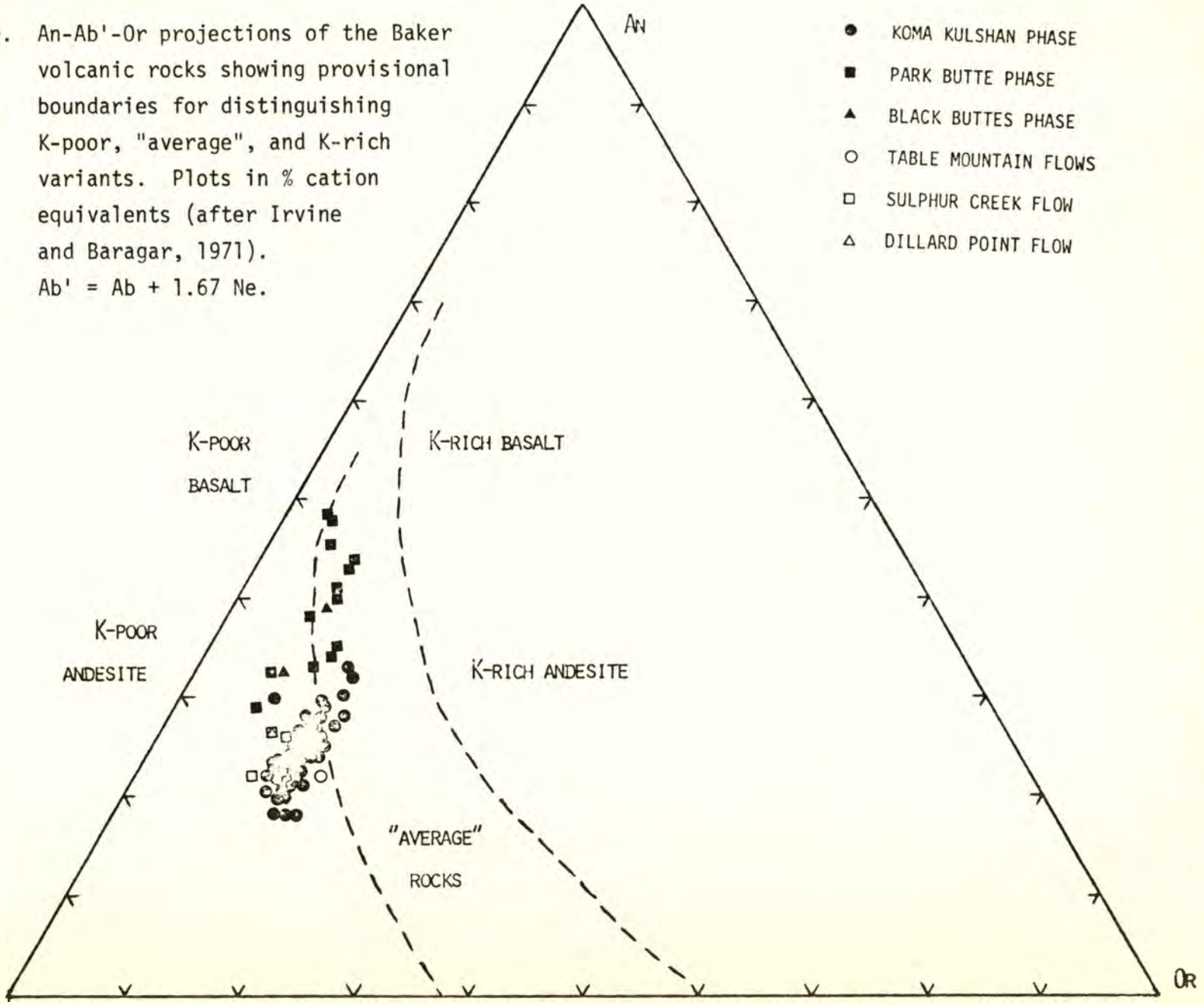


Figure 20. An-Ab'-Or projections of the Baker volcanic rocks showing provisional boundaries for distinguishing K-poor, "average", and K-rich variants. Plots in % cation equivalents (after Irvine and Baragar, 1971).
Ab' = Ab + 1.67 Ne.

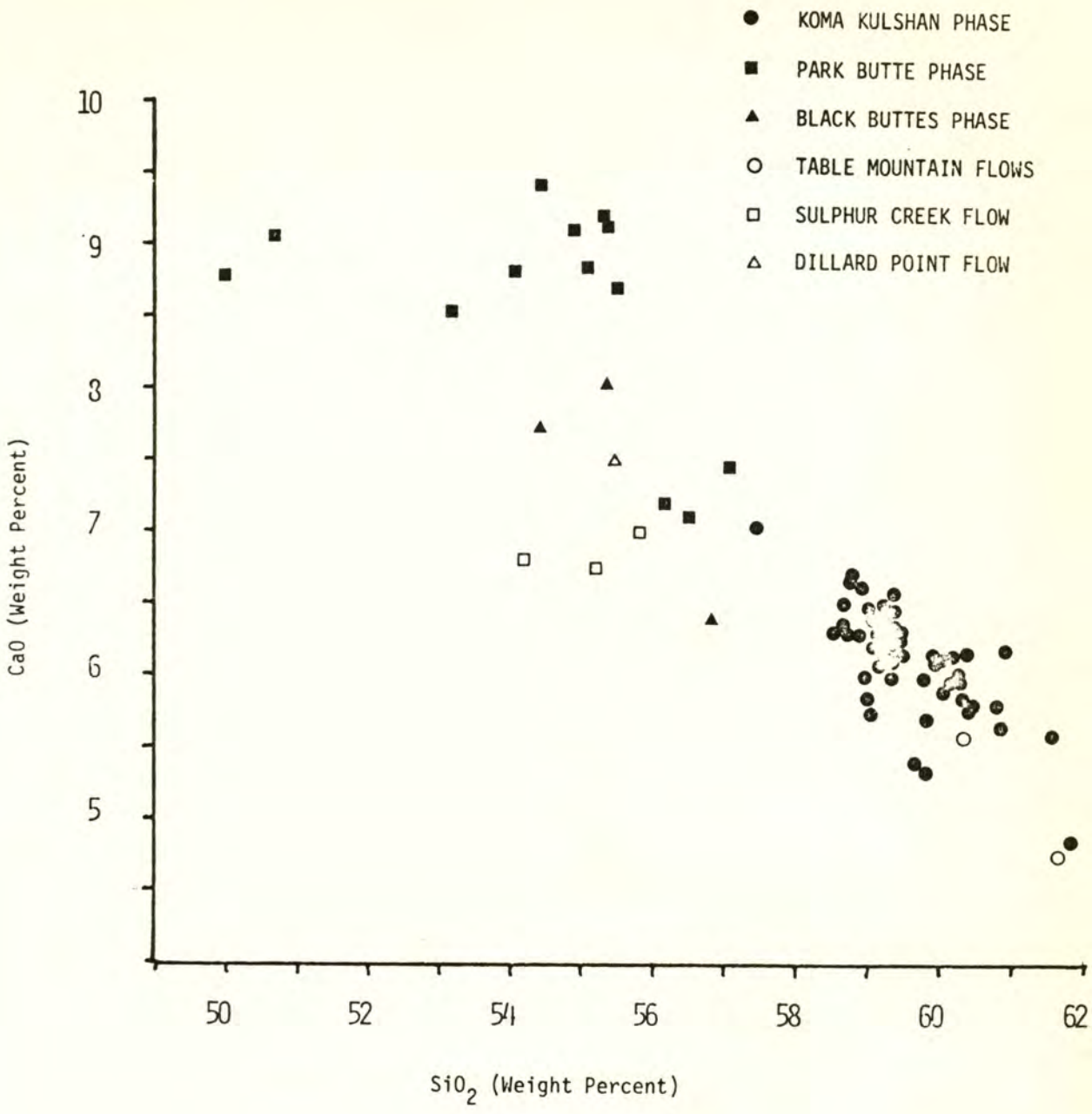


Figure 21. Variation diagram of CaO versus SiO_2.

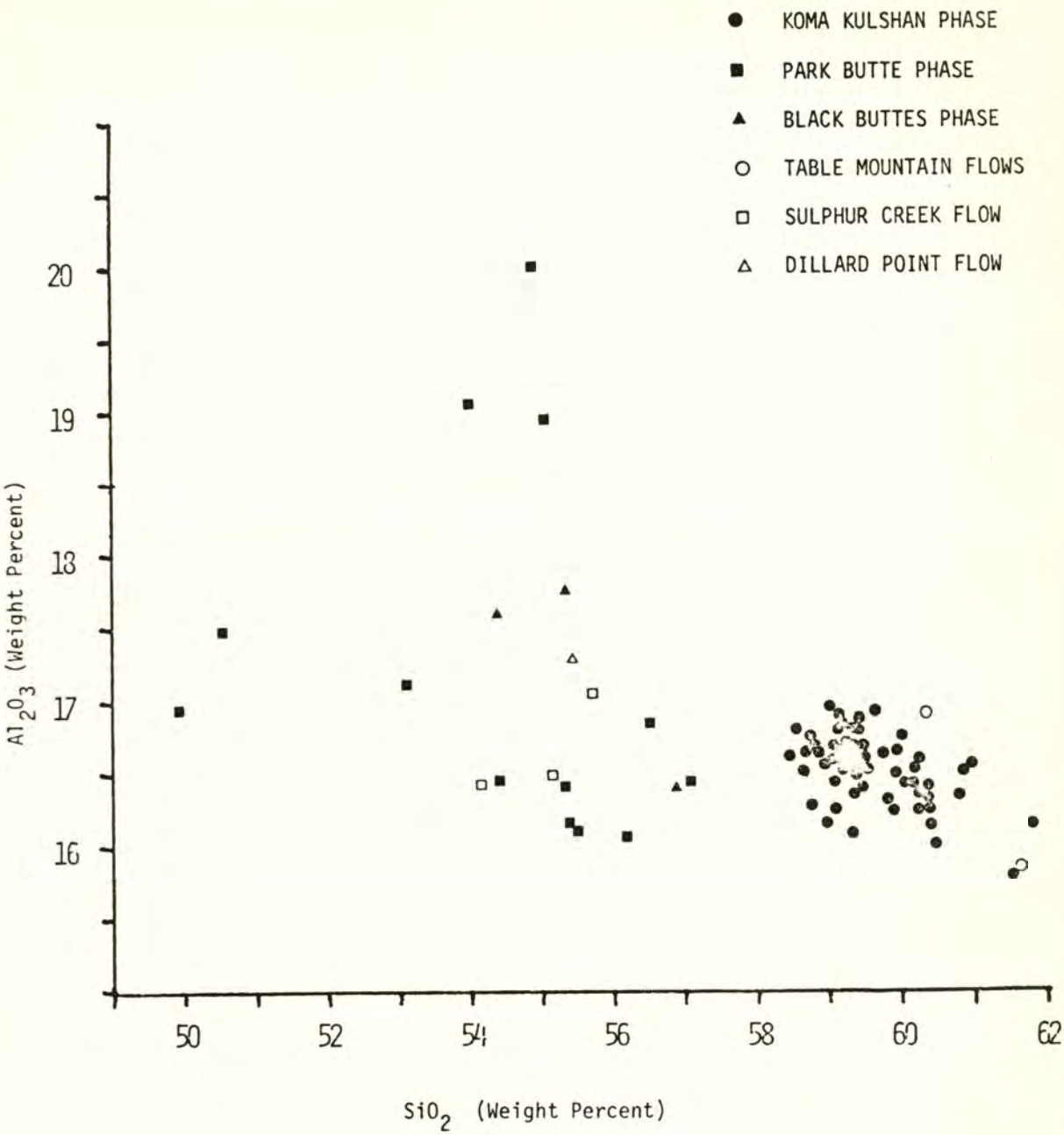


Figure 22. Variation diagram of Al_2O_3 versus SiO_2.

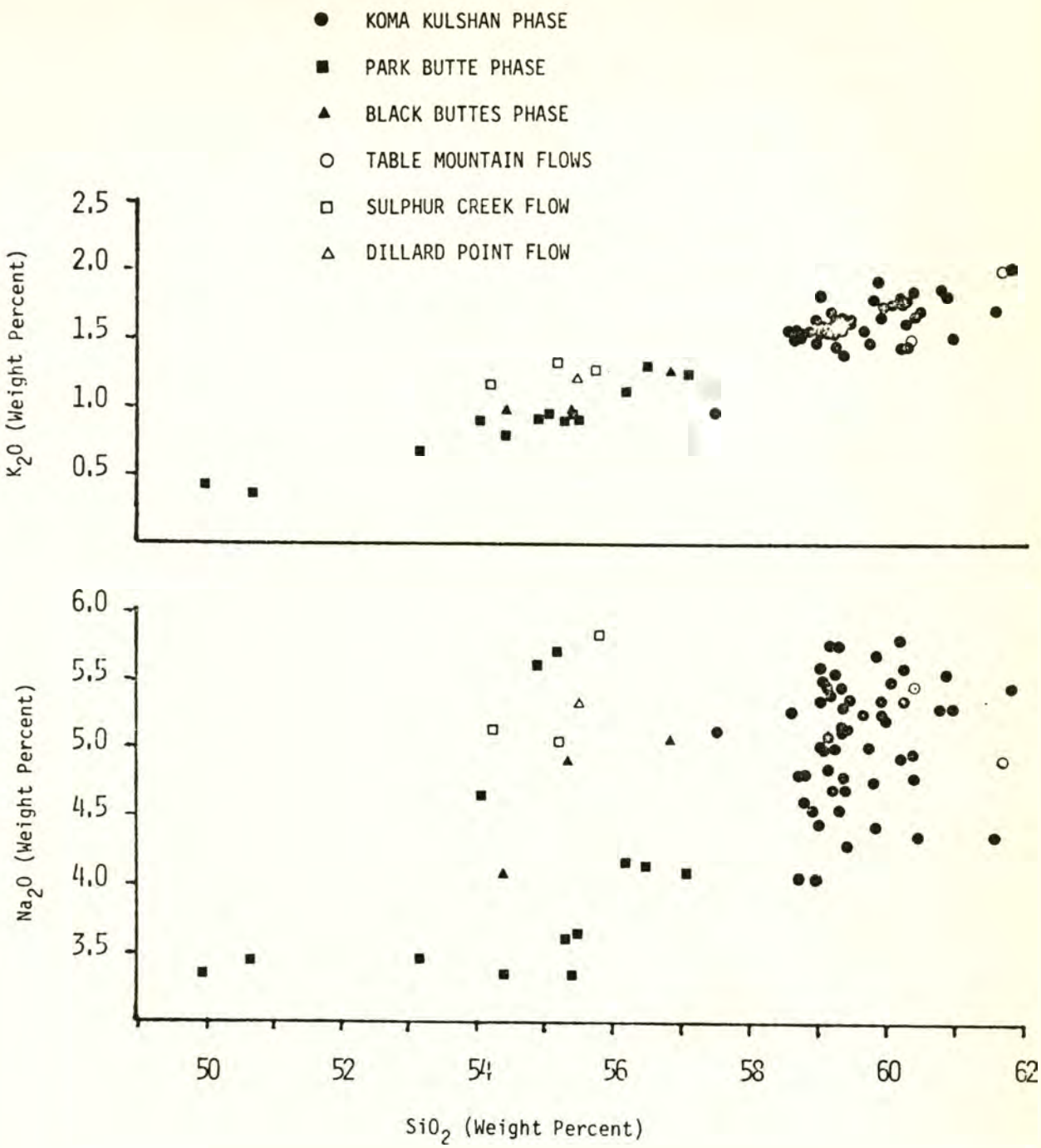


Figure 23. Variation diagram of K_2O versus SiO_2 (upper).

Figure 24. Variation diagram of Na_2O versus SiO_2 (lower).

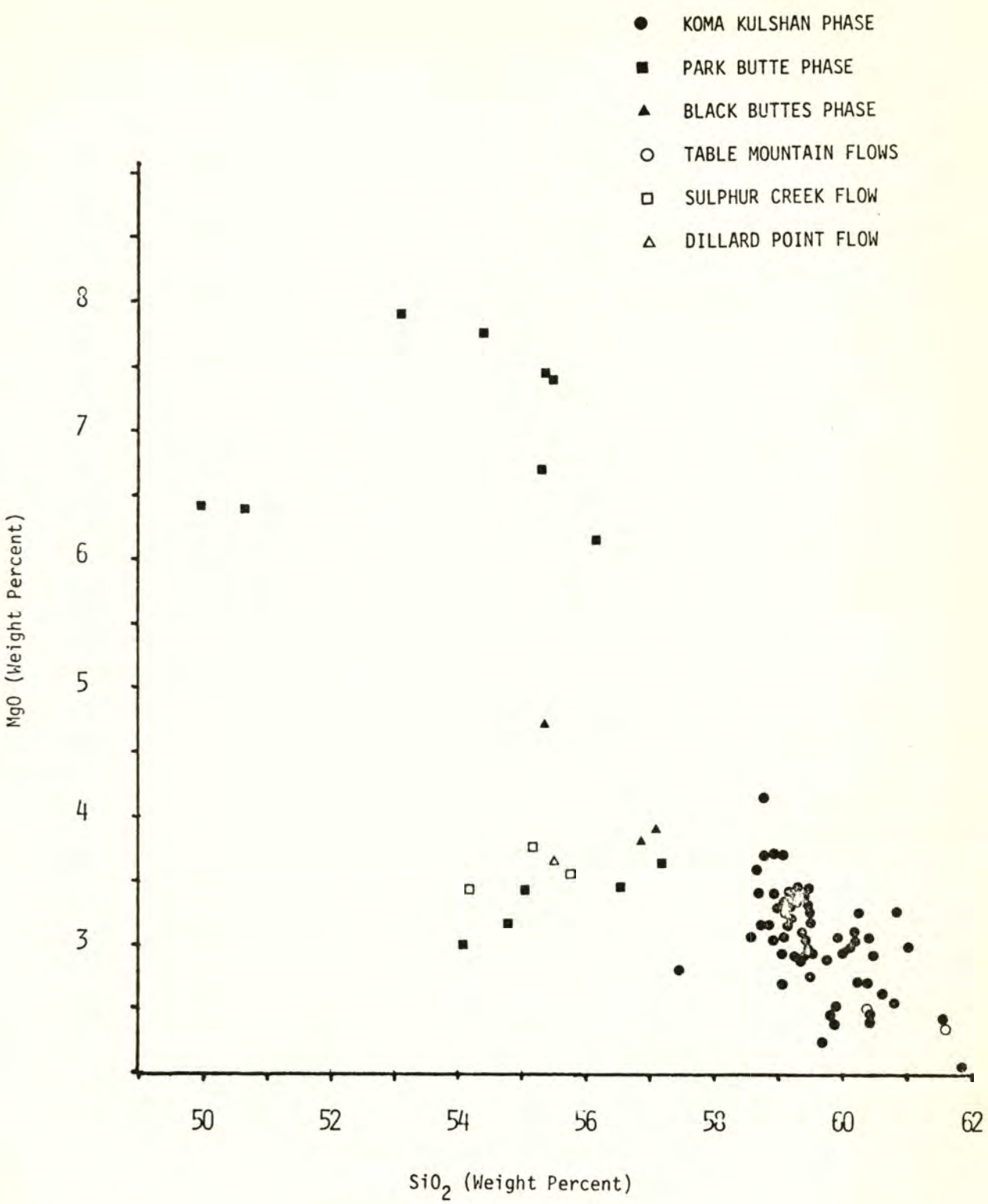


Figure 25. Variation diagram of MgO versus SiO_2.

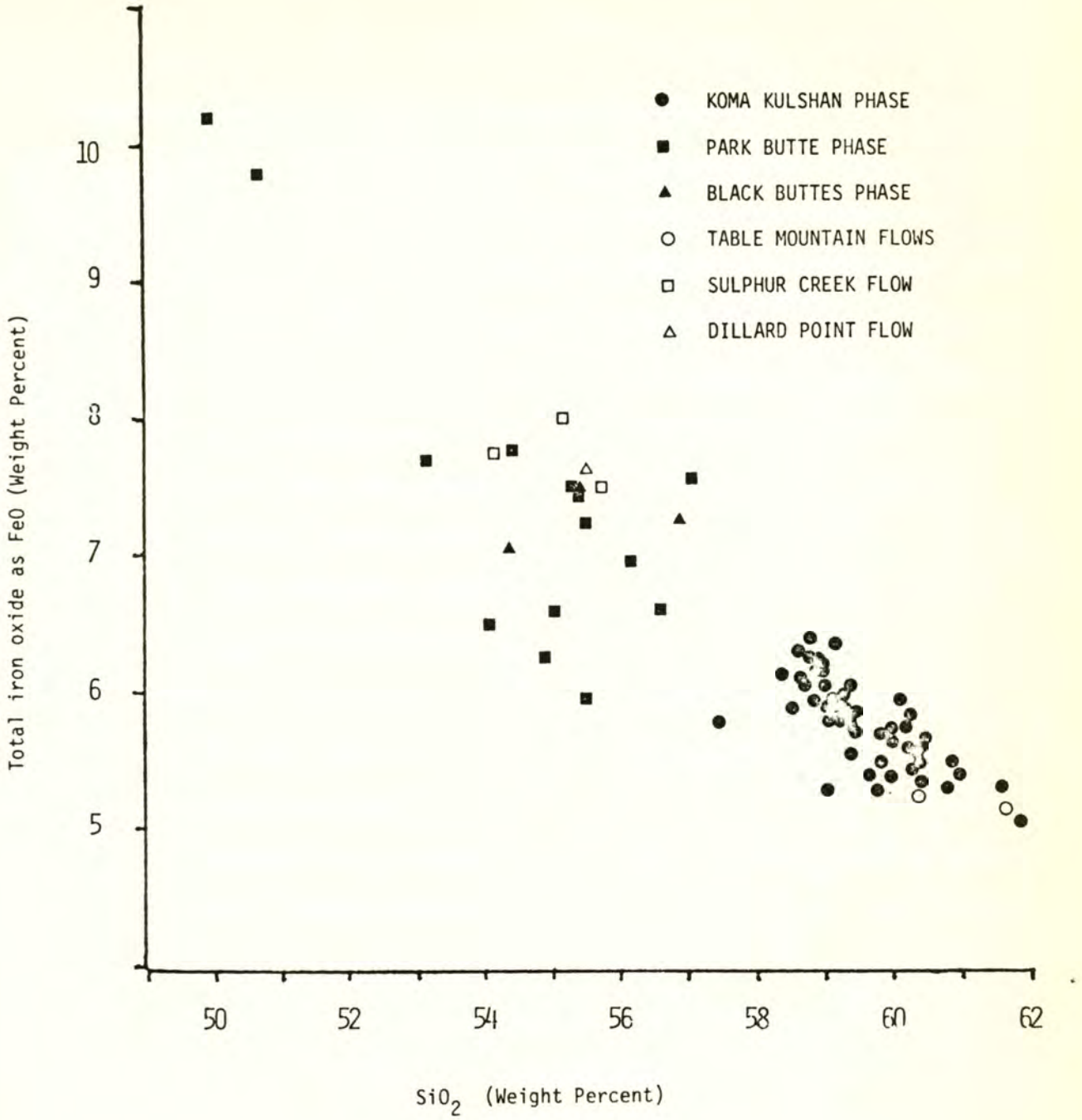


Figure 26. Variation diagram of total iron oxide versus SiO_2; iron oxide expressed as FeO.

Trends

Trends immediately apparent upon examination of the variation diagrams are:

1) The Koma Kulshan rocks are relatively well clustered (with the exception of Figure 23) and are high in silica and alkalies but low in iron, magnesium, and calcium compared to the Park Butte rocks, which are bi- or even tri-modal. Figures 21 and 26 show this trend especially well. Figure 23 shows more scatter due to the relative imprecision of Na_2O analysis.

2) Two samples from Table Mountain, which is topographically old, straddle the andesite - dacite line (Figures 18 and 19) and are not as basaltic as the old Park Butte volcanic rocks. The Table Mountain volcanic rocks are unusually silicic considering their relatively old age.

3) The Black Buttes volcanic rocks cluster between the Koma Kulshan and Park Butte volcanic rocks and closely resemble the more silica-rich Park Butte volcanic rocks (Unit B, Table 2).

4) Three samples from the upper Sulphur Creek flow (one of the youngest lavas of the Baker volcanic sequence) show a resemblance to the Black Buttes volcanic rocks and to the high-silica Park Butte samples. This and trend #2 lead me to concur with Stavert (1971) who noted that the anomalous Sulphur Creek composition does not suggest differentiation from a mafic magma. Differentiation should produce progressively more siliceous rocks with time.

5) A single sample from a flow at Dillard Point closely resembles the Sulphur Creek flow in every respect. Topography logically leads to the conclusion that the Dillard Point flow could not be a remnant of the Sulphur Creek flow, but chemistry and mineralogy are nearly identical.

6) In contrast to the findings of both Coombs and Stavert, at least three (Figure 19) and possibly as many as eight (Figure 17) samples can be considered basalts, depending on definitions of basalt. Significantly, all of the basalts are rocks of the Park Butte phase.

Stavert (1971) concluded that the Baker volcanic rocks are higher in K_2O than rocks from other Cascade volcanoes. In contrast comparison of Figure 22 with Ab' - An - or plot of the "average" rock from Cascade volcanoes (Irvine and Baragar, 1971) shows the Baker volcanic rocks to be mostly K-poor. The exception is the low-silica Park Butte rocks (unit A, Table 1), which are "average" to slightly K-poor. This conclusion must be made with caution because Figure 21 is also dependent upon Na_2O determination. Na_2O content is about average in comparison with rocks from other Cascade volcanoes. Again using diagrams from Irvine and Baragar (compiled from published chemical data from twelve Cascade volcanoes) Baker volcanics are in general low in CaO and slightly low in Al_2O_3 when compared to rocks of similar silica content. Koma Kulshan volcanic rocks are low in MgO but the low-silica Park Butte unit is relatively high in MgO. In general, Baker volcanic rocks are relatively high in total iron oxide in comparison with rocks from other Cascade volcanoes.

Probably the most important conclusion from examination of the diagrams presented here is that variation is not continuous nor, in general, smooth between the two or more groups of eruptives from the Baker volcanic center, at least based on the samples collected and analyzed from the south side of Mount Baker. The two major stratigraphic sections (Koma Kulshan phase and Park Butte phase) exhibit compositional coherency. Based on this and on field relationships, they are interpreted as eruptive groups which were extruded over time intervals which were short compared to the

lifetime of the volcanic center. The existence of distinct eruptive groups based on chemical analyses has been recently demonstrated for Mount Jefferson, Mount Rainier, and Mount Shasta (Condie and Swenson, 1973).

Chemical Composition as a Possible Mapping Tool

One of the original purposes of this study was to determine to what extent chemical analysis can be used to correlate flow remnants. Nearly all major accessible outcrops, as well as many minor exposures, were visited and sampled over the 15 km^2 field area. The completeness of the sampling and field observations is limited by extensive glacial and glacio-fluvial deposition and erosion, by permanent snowfields and glaciers at the higher elevations, and by luxuriant vegetation below about 1525 meters (5,000 feet).

Correlations among different samples were attempted using the COMPARE program (Mustoe, 1976), in which the weight percentages of all nine major oxides of all samples are entered into a computer as reference standards, after which any one sample can be compared to all of the reference standards stored in the computer. The computer automatically prints out the five best matches between all of the reference standards and the unknown.

In attempting to correlate discontinuous segments of flows, several conditions must hold: 1) chemistry of different flows varies by a factor which is greater than random analytical error; 2) chemistry within different portions of the same flow varies by a factor which is less than variation among flows; 3) chemical mobility during weathering has not significantly affected the bulk chemistry of the samples; 4) chemistry of different portions of the same flow varies less than the random sampling error; and 5) all of the chemical data should be considered.

Distinctive eruptive groups exist in the Baker volcanic rocks.

The relatively close clustering of the Koma Kulshan phase compared to the Park Butte phase suggests that chemical correlation may work best for the Park Butte rocks. However, based on field observations the Park Butte rocks can be divided into only a very small number of flows (about three) with certainty, a fact which limits the usefulness of the technique.

Best matches are given in Table 4. Initially, any samples having a mean relative deviation of less than about 0.025 (the value obtained from samples 8/5B and 8/5C, known to be from the same flow) were assumed to be from the same flow. Unfortunately, assumption (2) above does not hold. For example, samples 9/16F and 9/16E were observed in the field to definitely be from different flows, but the mean relative deviation between them is 0.0085, much less than the arbitrary value of 0.025. On the other hand, samples 9/9K and 9/9L are positively from the same flow, but the mean relative deviation between them is about 0.033. Part of the difference in the latter case may be due to the fact that 9/9K is much more weathered than 9/9L, but inspection of Table 3 (reference numbers 1 and 2) shows that 9/9K has lower alumina (a "stable" oxide) than 9/9L. Finally, samples 9/9A and 9/9P are from the same flow but their mean relative deviation is 0.106! Thus it appears that there is as much variation within a given flow as there is between or among different flows. This would not be evident if careful field observations had not been made.

The original goal of producing a map of detailed flow-by-flow boundaries had to be abandoned. Other possible means of comparison beyond the scope of this study, such as trace element and isotope distribution, may produce more accurate chemical matches between flow remnants. However, as has been noted, portions of stratigraphic sections within the Baker volcanic rocks exhibit compositional coherency and are interpreted as being eruptive

Table 4. Correlations Among Baker Volcanic Rocks Based on Chemical Analysis (COMPARE Program, Mustoe, 1976).

SAMPLE	BEST MATCHES	MEAN RELATIVE DEVIATION	SAMPLE	BEST MATCHES	MEAN RELATIVE DEVIATION
9/9K	9/9L	.0322	9/9I	7/7A	.0518
	8/5F	.174		9/9B	.0547
	8/5B	.206		9/3D	.0615
	8/6C	.212		9/3E	.0630
9/9L	8/9K	.0334	9/9A	9/9D	.0800
	8/5F	.185		9/3A	.109
	8/5D	.217		9/16G	.116
	8/5B	.223		9/9P	.116
8/5F	8/5B	.0436	7/7A	9/9I	.0486
	8/5C	.0551		9/9B	.0709
	8/5D	.0690		9/3E	.0813
	8/5A	.0751		7/6A	.0863
8/5D	8/5F	.0624	8/30A	9/3A	.0871
	8/5B	.0845		9/3F	.103
	8/5C	.102		9/9J	.104
	9/9N	.106		9/2I	.105
9/9J	8/5E	.0598	9/16G	9/17J	.0361
	8/5H	.0634		9/16J	.0500
	8/30A	.0942		9/2G	.0512
	8/11A	.111		9/9C	.0514
8/5B	8/5C	.0230	9/9P	9/16F	.0302
	9/9N	.0421		9/16E	.0305
	9/9M	.0429		7/7B	.0399
	8/5A	.0435		9/17J	.0486
8/11A	8/30D	.0120	9/2I	9/16C	.0135
	9/9J	.148		9/3F	.0164
	8/30A	.161		9/2E	.0170
	9/3A	.174		8/12B	.0181

Table 4 (contd.). Correlations Among Baker Volcanic Rocks Based on Chemical Analysis (COMPARE Program, Mustoe, 1976).

SAMPLE	BEST MATCHES	MEAN RELATIVE DEVIATION	SAMPLE	BEST MATCHES	MEAN RELATIVE DEVIATION
9/3E	9/2J	.0328	9/17L	9/2D	.0212
	9/3D	.0358		9/17O	.0236
	9/17M	.0441		7/6C	.0250
	9/2K	.0463		8/12B	.0254
9/17O	9/17C	.0196	9/16D	8/30F	.0266
	9/2D	.0223		9/17F	.0283
	9/2K	.0243		9/16I	.0283
	8/12B	.0252		9/2A	.0343
9/17A	8/12B	.0139	9/17M	9/17A	.0451
	9/2D	.0190		9/9R	.0454
	9/2K	.0193		9/3E	.0476
	9/2I	.0294		8/12B	.0495
9/2B	9/17L	.0278	9/9R	9/17A	.0447
	9/2J	.0317		9/17M	.0458
	9/2K	.0348		8/3D	.0498
	7/6C	.0379		9/3E	.0510
9/2J	9/17L	.0262	7/6C	9/17L	.0239
	9/3E	.0288		9/2K	.0287
	9/3D	.0300		9/2F	.0299
	9/2B	.0322		8/30B	.0306
8/12B	9/2D	.00991	9/3B	9/3F	.0306
	9/17A	.0137		9/2E	.0317
	9/2K	.0188		9/17D	.0342
	9/2I	.0188		8/30E	.0358
9/3D	9/2J	.0308	9/17D	9/3F	.0205
	9/2K	.0322		9/2E	.0271
	9/3E	.0342		9/16A	.0305
	7/6B	.0405		9/2H	.0310

Table 4 (contd.). Correlations Among Baker Volcanic Rocks Based on Chemical Analysis (COMPARE Program, Mustoe, 1976).

SAMPLE	BEST MATCHES	MEAN RELATIVE DEVIATION	SAMPLE	BEST MATCHES	MEAN RELATIVE DEVIATION
9/16C	9/2C	.0129	9/9M	9/9N	.0125
	9/2I	.0132		8/5C	.0427
	9/2E	.0203		8/5A	.0465
	9/3F	.0208		8/5B	.0579
9/2D	8/12B	.00173	8/5C	8/5B	.0230
	9/2K	.0173		9/9N	.0421
	9/17A	.0184		9/9M	.0429
	9/17O	.0216		8/5A	.0435
9/17B	7/6B	.0143	7/6A	8/4A	.0506
	8/30E	.0172		7/7A	.0677
	9/17N	.0174		9/9I	.105
	9/2C	.0196		8/5H	.116
7/6B	9/17B	.0148	8/5A	9/9N	.0385
	8/30E	.0204		8/5C	.0410
	9/17N	.0215		9/9M	.0439
	9/2D	.0256		8/5B	.0551
8/5E	9/9J	.0565	9/9N	9/9M	.0121
	8/5H	.0588		8/5A	.0405
	8/30A	.108		8/5C	.0407
	8/11A	.157		8/5B	.0550
8/5H	9/9J	.0553	7/6D	7/6A	.0402
	8/5E	.0553		8/4A	.0515
	8/30A	.108		7/7A	.0934
	7/6A	.127		9/9I	.107
8/4A	7/6A	.0508	8/30D	8/11A	.134
	7/7A	.0891		9/9A	.135
	9/2J	.107		9/3A	.147
	9/9I	.109		9/9D	.154

Table 4 (contd.). Correlations Among Baker Volcanic Rocks Based on Chemical Analysis (COMPARE Program, Mustoe, 1976).

SAMPLE	BEST MATCHES	MEAN RELATIVE DEVIATION	SAMPLE	BEST MATCHES	MEAN RELATIVE DEVIATION
9/3A	9/9P	.0568	9/2F	8/30B	.0719
	9/17J	.0622		9/2C	.0200
	9/16G	.0658		9/17B	.0202
	9/16J	.0683		9/16C	.0234
8/6A	9/9M	.0996	9/16J	9/2A	.0182
	9/9I	.102		1/17J	.0244
	9/9B	.103		9/16A	.0248
	9/9N	.105		9/2G	.0280
9/9B	9/9I	.0547	9/3C	9/17C	.0275
	7/7A	.0775		9/17K	.0376
	9/3E	.0892		9/17O	.0379
	9/9R	.103		9/2G	.0414
9/2C	9/16C	.0126	9/2A	9/16A	.0137
	9/2I	.0189		9/16J	.0181
	9/17N	.0191		9/17E	.0230
	9/17B	.0205		9/17J	.0252
9/2K	9/2D	.0173	8/30E	9/17N	.0123
	8/12B	.0182		9/17B	.0178
	9/17A	.0186		7/6B	.0213
	9/17O	.0234		9/2C	.0221
9/16A	9/2A	.0132	8/3F	9/2E	.00753
	9/17E	.0172		9/2I	.0167
	9/3F	.0220		9/17D	.0197
	9/16J	.0236		9/2H	.0204
8/30B	9/2F	.0188	9/9Q	9/16F	.0403
	9/2C	.0229		9/16E	.0437
	9/17B	.0271		7/7B	.0494
	9/16C	.0273		9/9D	.0557

Table 4 (contd.). Correlations Among Baker Volcanic Rocks Based on Chemical Analysis (COMPARE Program, Mustoe, 1976).

SAMPLE	BEST MATCHES	MEAN RELATIVE DEVIATION	SAMPLE	BEST MATCHES	MEAN RELATIVE DEVIATION
9/17C	9/17K	.0129	8/30C	7/23B	.0592
	9/17O	.0193		9/9F	.0718
	9/3C	.0268		9/9D	.0733
	9/2D	.0276		9/16D	.0737
9/2G	9/2A	.0269	9/9D	9/9E	.0572
	9/16J	.0287		9/9G	.0619
	9/17K	.0324		9/9C	.0650
	9/16A	.0325		9/9F	.0680
9/2E	9/3F	.00743	7/7B	9/16E	.0233
	9/2I	.0169		9/16B	.0233
	9/2H	.0183		9/16F	.0285
	9/16C	.0209		9/9P	.0396
9/17J	9/16J	.0254	9/16I	9/17G	.0173
	9/2A	.0272		9/17F	.0277
	9/16G	.0341		9/16D	.0280
	9/9H	.0361		8/30F	.0345
9/17K	9/17C	.0130	9/9C	9/9F	.0328
	9/17E	.0163		9/9E	.0411
	9/16A	.0228		9/9H	.0497
	9/17O	.0261		9/16G	.0538
9/17N	8/30E	.0122	9/17E	9/16A	.0165
	9/17B	.0176		9/17K	.0167
	9/2C	.0183		9/2A	.0213
	7/6B	.0216		9/2E	.0259
9/9G	9/9E	.0344	8/30F	9/16D	.0255
	9/9H	.0481		9/17H	.0301
	9/16I	.0553		9/16I	.0326
	9/9D	.0597		9/17F	.0378

Table 4 (contd.). Correlations Among Baker Volcanic Rocks Based on Chemical Analysis (COMPARE Program, Mustoe, 1976).

SAMPLE	BEST MATCHES	MEAN RELATIVE DEVIATION	SAMPLE	BEST MATCHES	MEAN RELATIVE DEVIATION
9/2H	9/2E	.0185	9/17F	9/17G	.0213
	9/3F	.0202		9/16I	.0269
	9/2I	.0284		9/16D	.0271
	9/17E	.0291		9/17H	.0278
8/12A	9/16H	.0246	9/16F	9/16E	.0123
	8/30E	.0337		7/7B	.0280
	9/2H	.0363		9/9P	.0288
	9/17N	.0370		9/16B	.0309
9/17I	9/17E	.0255	9/9F	9/9C	.0325
	9/16H	.0357		9/9E	.0347
	8/6C	.0359		9/16D	.0468
	9/17K	.0397		9/16I	.0511
9/16E	9/16F	.0121	9/17G	9/16I	.0167
	7/17B	.0225		9/17F	.0210
	9/16B	.0253		9/17H	.0316
	9/9P	.0291		9/16D	.0371
9/16H	8/12A	.0261	9/9H	9/9E	.0355
	9/17I	.0366		9/17J	.0366
	9/2H	.0367		9/2A	.0382
	9/17D	.0380		9/17F	.0414
8/6D	9/16B	.0314	9/17H	9/17F	.0274
	8/6C	.0316		8/30F	.0297
	9/16F	.0380		9/17G	.0312
	9/16E	.0381		9/16I	.0357
7/23B	7/7B	.0427	8/6C	8/6D	.0298
	7/16B	.0484		9/17I	.0372
	9/9F	.0520		9/17H	.0472
	9/9C	.0532		9/17F	.0508

Table 4 (contd.). Correlations Among Baker Volcanic Rocks Based on Chemical Analysis (COMPARE Program, Mustoe, 1976).

SAMPLE	BEST MATCHES	MEAN RELATIVE DEVIATION
9/16B	7/7B	.0226
	9/16E	.0249
	9/16F	.0295
	8/6D	.0331
9/9E	9/9G	.0333
	9/9F	.0346
	9/9H	.0399
	9/9C	.0400
7/23A	9/17H	.0695
	9/16I	.0749
	9/9E	.0766
	9/17G	.0791

groups. While confident mapping of individual flows based on chemistry does not appear to be possible at this point, coherency of eruptive groups shows that geochemical mapping may be done in a broader sense. Specifically, variation diagrams may be used to classify individual samples from the Baker volcanic rocks in the study area as either belonging to the Park Butte phase or the Koma Kulshan phase.

Compositional variations within the Koma Kulshan group do not appear to be systematically related to stratigraphic position within the group. Ranges in variation within the group are typically of the same order of magnitude as those observed within individual flows in the group. In addition, intra-group compositional variations do not appear to be accompanied by parallel observable mineralogical variations.

Discussion

Mount Rainier, Mount Shasta, Mount Hood, Mount Jefferson, and Mount Baker are commonly cited as exhibiting coherent chemical trends (McBirney, 1968). However, from the data summarized herein as well as for Rainier, Shasta, and Jefferson (Condie and Swenson, 1973), a simple classification into divergent and coherent types for Cascade volcanoes is an oversimplification. Inadequate sampling can produce apparently smooth and continuous variation diagrams (See Stavert, 1971). The results of this study indicate that a large number of samples are needed to identify discontinuities on variation diagrams. Interpretations of variation diagrams based on only a few samples should be considered questionable.

Studies by Hopson (1972) on the origin of coherent and divergent suites point to two important factors: 1) liquid differentiation (diffusion) or gas transfer which move H_2O, silica, and alkalies gradually toward the

top of magma columns, and 2) rate of magma ascent. Hopson believes that magma which moves directly to the surface erupts as coherent magma, while magma that ascends haltingly or stagnates in shallow chambers fractionates to varying degrees, depending on rate of differentiation and length of lag time before eruption. In this case a divergent suite results. Either suite can originate from magma which is initially similar (andesite with silica content of about 61-62%).

The Baker volcanic rocks show the following characteristics of a divergent suite: 1) moderately wide range of rock types, with silica content ranging from about 50% to about 62%; 2) intratelluric plagioclase phenocrysts, patchy zoning, and oscillatory zoning, all of which may indicate pauses in magma ascent (Vance, 1962, 1965; Wise, 1969); 3) more explosive early eruptive activity; 4) recent (late stage?) flank eruption of more mafic lava (Sulphur Creek flow).

Characteristics of a coherent suite in the Baker volcanic rocks include: 1) relative scarcity of basalt, almost complete absence of dacite, and complete absence of rhyolite; 2) uniform composition of younger andesitic flows (Koma Kulshan phase), while the older lavas are more basaltic (olivine basalt in divergent suites is thought to be a liquid differentiation product of andesitic magma and to be a late stage or both early and late-stage but not middle-stage, product (McBirney, 1968; Hopson, 1972)).

Review of the above observations in light of theories of andesite petrogenesis indicate that the Baker volcanic rocks do not belong to a coherent suite as has previously been noted by McBirney (1968) and Stavert (1971). The Baker volcanic rocks are transitional between coherent and diverent suites as defined by McBirney.

Speculation on the Petrogenesis of Baker Magma

Hypotheses for the origin of Cascade andesites have been reviewed by Stavert (1971), Church and Tilton (1973), and Condie and Swenson (1973), among others. While no attempt will be made here to provide a complete overview of recent theoretical and empirical evidence for or against the numerous hypotheses espoused by various workers, selected work will be discussed particularly as it relates to the data presented in this report.

Chemical data plotted in Figures 16 through 27 show a separation which is interpreted as evidence of at least two main eruptive groups. Similar diagrams for Mount Shasta, Mount Jefferson, and Mount Rainier are interpreted as evidence agains progressive fractional crystallization (Condie and Swenson, 1973). Wise (1969) flatly states that the Mount Hood lava did not differentiate from high-alumina basalt magma, but that olivine basalt magma did differentiate to form andesite, that all olivine basalts at Mount Hood were differentiated or contaminated prior to eruption, and that several eruptive groups were erupted through time, some of which are related to a basalt parent and others to a primary andesite. In complete contrast, isotopic and trace element data from andesite and high-alumina basalt in the Cascades lead Church and Tilton (1973) to conclude that the andesite and high-alumina basalt can be derived from a common source, and that andesite can be derived by differentiation of high-alumina basalt magma.

In the opinion of this writer, the data herein presented do not give conclusive evidence for or against fractional crystallization from a single parent magma as the source of the two main eruptive groups of the Baker volcanic rocks. The data do however, seem to support Ewart's (1976) contention that the majority of orogenic basaltic and andesitic magma is

modified (if not derived) by crystal fractionation processes dominated by relatively calcic plagioclase. Ewart's data indicate that the modal dominance of plagioclase, when considered in light of experimental studies such as those of Eggler (1972), show that the magmas were strongly water under-saturated or perhaps water-saturated at very low pressures (less than 0.5 kbar) at the time of phenocryst crystallization. Water under-saturation is consistent with the mineralogy observed in the Baker volcanics. Use of mixing equations (Wright, 1974; Wright and Doherty, 1970) may be useful in understanding the extent to which magmatic differentiation may have been important.

Condie and Swenson (1973) postulate a fractional crystallization model for stratovolcano growth in which several magma chambers may receive magma from the same mantle source, but the separate chambers are tapped sporadically and at different stages in their fractionation history, thus producing non-systematic compositional trends with time. While such a mechanism is consistent with the eruptive group, interpretation of the Baker volcanic rocks, trace element data compiled from several Cascade volcanoes limit the role of fractional crystallization in producing the diversity of rock types found in the Cascades (Taylor, 1969). Trace element data for Baker rocks do not support an origin by fractional crystallization (Stavert, 1971).

A multistage model in which calcic and calc-alkaline magma is derived from mantle material by three or more stages of partial melting, and in which crustal materials play an insignificant role, is offered by Church and Tilton (1973) as the best explanation of the isotopic and trace element data from Cascade volcanoes. A virtually identical model (Condie and Swenson, 1973) involves production of magma from various degrees of melting of some combination of peridotite, amphibolite, or eclogite in or above a

subduction zone under conditions ranging from hydrous to anhydrous. The magma is segregated into sub-crustal chambers and, periodically, a relatively small volume of magma moves upward over a period of several months and is extruded forming an "eruptive group", with probably little or no time spent in shallow fractionation chambers prior to eruption. Composition of the eruptive group may be controlled by such factors as varying degrees of melting of mantle source materials, and changes in water content due to variations in the rate of eruption (resulting in water loss) or in the rate at which water migrates into the source area from surrounding mantle.

Even without considering isotope or trace element data, the preceding model does not wholly explain the origin of the Baker volcanic rocks. A significant problem is posed by the "abrupt ascent" condition of Condie and Swenson (Church and Tilton make no mention of rate of ascent). Volcanological studies from volcanoes representing all compositional ranges, sizes, and tectonic environments show that the abrupt ascent (several months) model is incorrect; there is a gradual inflation or other distortion of a relatively near-surface (a few kilometers deep) reservoir prior to eruption (Macdonald, 1972). The available seismic, experimental petrological, and volcanogical evidence (summarized by Macdonald, 1972) indicates that magma remains in a near-surface reservoir for times at least of the order of the intervals between eruptions and that the crustal reservoir probably is continuously molten throughout the lifetime of the activity of the volcano (of the order of 10^5 years). Time-volume considerations in light of crystallization time strongly suggest magma mixing (Anderson, 1976), but the mixed magmas may be so similar in composition as to negate "contamination" effects.

Evidence based on textural and field relationships of the evolving composition of melt in magma systems, combined with the heat budget arguments advanced by Bowen (1928), provide compelling evidence for magma mixing, in the opinion of Anderson (1976). Anderson feels that mixing of basaltic and silicic melts may be the dominant process by which contamination occurs and may play a significant or even dominant role in the origin of many andesites. However, his evidence suggests that andesitic and more silicic magmas develop, segregate, and crystallize in vapor-saturated crustal environments rather than in the mantle. Evidence against magma mixing for the Baker lavas includes the apparent low water content of the magma, the lead and strontium isotope studies in the Cascades which cast doubt on all of the various mixing models proposed for andesite genesis (Church and Tilton, 1973), and trace element data for twelve Baker volcanic rocks which do not support mixing (Stavert, 1971). The extent to which magma mixing may have occurred, if at all, is not clear because the best evidence for this phenomenon is reputedly found in glassy tephra (Anderson, 1976). Electron microprobe analysis of glassy tephra such as the tuff found at Crag View would be a logical next step in the ongoing debate about the significance of magma mixing.

The Baker magmas, particularly those forming the Koma Kulshan phase, may have resided for a long time in a near-surface magma chamber, and available evidence suggests that there was much turbulence and little if any crystal settling. Volatiles were not concentrated near the top of the chamber, probably because the magma was anhydrous or at least undersaturated with water. Eruption probably took place quickly in both eruptive groups, one of the major differences being the rate of effusion: low for the Black Buttes, high for Koma Kulshan.

Probably the best recent commentary on the many models for magma generation in orogenic environments is that of McBirney (1976): "It is impossible to choose between the many proposed models for magma generation at convergent plate boundaries without more information on the quantitative aspects of magma generation and the geochemical balance of the system as a whole. There is a clear need for more data on the relative abundance of rock types in different geologic settings and on the rates at which these rocks have been produced over extended periods of time." While thinking it premature to favor any hypothesis of magma origin, McBirney notes that wherever large volumes of calc-alkaline rocks are erupted on a well-defined volcanic front, basalt is by far the dominant rock type. In addition, andesite is proportionally much more abundant in the northern and southern Cascades where volcanoes are built upon thick sialic crust. These factors are viewed by McBirney as strong evidence against a primary andesitic magma.

In summary, the data presented here indicate that the Baker volcanic center has undergone a complex developmental history and that extensive sampling and field studies are necessary to unravel this history in detail. After individual eruptive groups are defined, mapped, and accurately measured, absolute dating and trace element and isotopic studies should make possible the reconstruction of a time-dependent, quantitative model for the evolution of the Baker volcanic center, and to construct possible scenarios for any future activity.

APPENDIX

ANALYTICAL PROCEDURE

Sample Preparation for Chemical Analysis

A portion of each rock sample was broken off with a hydraulic press and the remainder saved for hand specimen and petrographic study. The portion removed was crushed to gravel size in a steel jaw crusher and then ground to -200 mesh powder in a Spex Industries tungsten carbide ball mill, operated for 20 minutes. The rock powder was stored in polyethylene bottles prior to EDAX-EXAM analysis.

Ten available samples of Baker volcanic rocks from a previous study (Stavert, 1971) were re-ground inasmuch as the prepared powders were too coarse.

A portion of each powder was pressed into a 2.5 cm diameter wafer using a hydraulic press operating at a pressure of 20 tons. A protective backing layer of boric acid and cellulose in equal amounts was added to make the sample more durable, again using 20 tons pressure.

Energy-Dispersive X-ray Fluorescence Analysis

Prepared samples were analyzed using energy-dispersive x-ray fluorescence methods with an EDAX-EXAM, Model 704, spectrophotometer. Elements included in the analysis are Na, Mg, Al, Si, K, Ca, Ti, Fe, and Mn. Each sample was analyzed for 200 seconds, using a gold target x-ray tube operated at a tube voltage of 10.0 kilovolts and a tube amperage of 256 microamps.

Precision and Accuracy

There are three main sources of error during EDAX-EXAM analysis.

They are:

1. Poor reproducibility (precision), where replicate samples of a single rock yield different results. This may be due to inadequate grinding, sloppy preparation of wafers, or other factors.
2. Instrument drift due to short or long-term electronic drift or unstable x-ray tube output.
3. Errors during EDIT data processing (accuracy). This is probably the largest source of error and is caused by relative dissimilarities in mineralogy and bulk chemistry of the unknown samples to the rock standards used to calibrate the computer.

1. Precision

Considerable effort was expended on ascertaining the reproducibility of the analytical results. Six runs were made on independently prepared wafers of three different samples. The results, which are listed in Table 5, show excellent agreement among the multiple runs. The probable error in the individual determinations was found to be much less than 1% relative standard deviation both for totals and for most of the individual oxides. The largest relative standard deviation is for Na_2O, MgO, TiO_2, and MnO.

Variation in intensity values due to slight differences in alignment of the three sample holders in relation to the x-ray tube and detector window was compensated for by utilizing the EXAM normalization method (Mustoe, 1977).

2. Instrument Drift

Long-term drift is partially compensated for by the automatic drift-correction feature, in which a synthetic sample is analyzed and compared to original drift standards JB-1 and BR to determine instrument drift at the time of analysis. Effects of long-term drift were also

Table 5. Comparison of Multiple EDAX Analyses[1] of Selected Samples

SAMPLE	8/5D							
REFERENCE NO.[2]	4							
ANALYSIS NO.	1	2	3	4	5	6	MEAN	STD DEV.	REL. STD DEV. (%)
Na_2O	2.61	2.69	2.13	2.29	2.73	2.62	2.51	0.11	4.33
MgO	7.73	7.72	7.83	7.75	7.89	7.90	7.80	0.036	0.46
Al_2O_3	16.85	16.85	16.84	16.84	16.86	16.86	16.85	0.0040	0.024
SiO_2	52.45	52.44	52.34	52.35	52.41	52.55	52.42	0.034	0.065
K_2O	0.71	0.70	0.69	0.70	0.70	0.70	0.70	0.0028	0.40
CaO	10.29	10.27	10.35	10.31	10.30	10.42	10.32	0.024	0.23
TiO_2	0.95	0.94	0.98	0.96	0.98	0.99	0.967	0.0088	0.91
Fe_2O_3[3]	10.48	10.50	10.61	10.59	10.62	10.61	10.57	0.028	0.26
MnO	0.07	0.07	0.06	0.07	0.07	0.07	0.068	0.0018	2.67
TOTAL	102.14	102.18	101.83	101.86	102.56	191.62	102.03	0.15	0.15

[1]Two analyses were performed in each of the three chambers on the EDAX analyzer, and the intensity values were then corrected using the chamber correction routine (Mustoe, 1977). These analyses are based on Stavert's (1971) lavas as standards.

[2]From Table 3 (page 54).

[3]Total iron oxide as Fe_2O_3.

Table 5 (contd.). Comparison of Multiple EDAX Analyses[1] of Selected Samples

SAMPLE	8/30C								
REFERENCE NO.[2]	71								
ANALYSIS NO.	1	2	3	4	5	6	MEAN	STD DEV.	STD DEV. (%)
Na_2O	4.199	3.44	3.62	3.69	3.75	3.16	3.64	0.15	4.24
MgO	2.20	2.08	1.99	2.13	2.10	2.19	2.11	0.035	1.64
Al_2O_3	16.73	16.77	16.72	16.74	16.74	16.79	16.75	0.12	0.070
SiO_2	57.48	57.25	57.59	57.49	57.41	57.26	57.41	0.061	0.11
K_2O	1.71	1.71	1.73	1.73	1.72	1.73	1.72	0.0044	0.26
CaO	5.85	5.90	5.85	5.85	5.88	5.84	5.86	0.010	0.18
TiO_2	0.43	0.44	0.42	0.42	0.44	0.43	0.43	0.004	0.93
Fe_2O_3[3]	7.41	7.45	7.39	7.38	7.44	7.40	7.41	0.012	0.17
MnO	0.04	0.04	0.04	0.03	0.04	0.04	0.038	0.0018	4.76
TOTAL	96.05	95.08	95.33	95.46	95.52	94.84	95.38	0.18	0.19

[1]Two analyses were performed in each of the three chambers on the EDAX analyzer, and the intensity values were then corrected using the chamber correction routine (Mustoe, 1977). These analyses are based on Stavert's (1971) lavas as standards.

[2]From Table 3 (page 65).

[3]Total iron oxide as Fe_2O_3.

Table 5 (contd.). Comparison of Multiple EDAX Analyses[1] of Selected Samples

SAMPLE	9/16C								
REFERENCE NO.[2]	48								
ANALYSIS NO.	1	2	3	4	5	6	7	8	9
Na_2O	3.45	3.41	3.91	3.30	3.37	3.03	3.41	0.13	3.75
MgO	2.76	2.72	2.94	2.79	2.79	2.89	2.81	0.037	1.32
Al_2O_3	16.59	16.55	16.58	16.53	16.54	16.54	3.41	0.13	3.75
SiO_2	57.93	58.20	57.85	58.18	57.99	58.16	58.05	0.066	0.11
K_2O	1.53	1.55	1.55	1.56	1.55	1.54	1.55	0.0046	0.30
CaO	6.62	6.64	6.76	6.72	6.67	6.69	6.68	0.023	0.35
TiO_2	0.44	0.43	0.46	0.47	0.46	0.45	0.45	0.0066	1.46
Fe_2O_3[3]	7.48	7.42	7.55	7.50	7.56	7.49	7.50	0.023	0.30
MnO	0.04	0.04	0.04	0.04	0.04	0.04	0.04	-	-
TOTAL	96.84	96.96	97.64	97.09	96.97	96.83	97.05	0.14	0.14

[1]Two analyses were performed in each of the three chambers on the EDAX analyzer, and the intensity values were then corrected using the chamber correction routine (Mustoe, 1977). These analyses are based on Stavert's (1971) lavas as standards.

[2]From Table 3 (page 61).

[3]Total iron oxide as Fe_2O_3.

by running all of the samples in a two week period.

Additional compensation can be achieved by running each wafer several times and averaging the intensity values. Results for a sample of basalt have been tabulated in Table 6.

TABLE 6. Multiple Runs of Same Wafer of JB-1 (data courtesy of George Mustoe, W.W.S.C. Geology Department).

OXIDE	RELATIVE STANDARD DEVIATION (%)	
	Analyzed 4 times	Analyzed 37 times
Na_2O	1.49	0.43
MgO	1.58	0.36
Al_2O_3	0.68	0.20
SiO_2	2.78	0.51
K_2O	0.92	0.24
CaO	0.64	0.19
TiO_2	0.85	0.23
Total iron	0.65	0.21
MnO	0.68	0.27

3. Errors During Data Processing (Accuracy)

Unknown samples were compared to two sets of standards. One set, consisting of widely-used standards from the United States and abroad, is listed in Table 7.

TABLE 7. International Mafic Rock Standards

Sample	Rock Type	Country of Origin
USGS-W1	Diabase	United States
USGS-BCR-1	Basalt	United States
USGS-AGV-1	Andesite	United States
USGS-GSP	Granodiorite	United States
GSJ-JB-1	Basalt	Japan
GSJ-JG-1	Granodiorite	Japan
CRPG-BR	Basalt	France
ZGI-GM	Granite	Germany
ZGI-BM	Basalt	Germany
NIM-M	Norite	South Africa

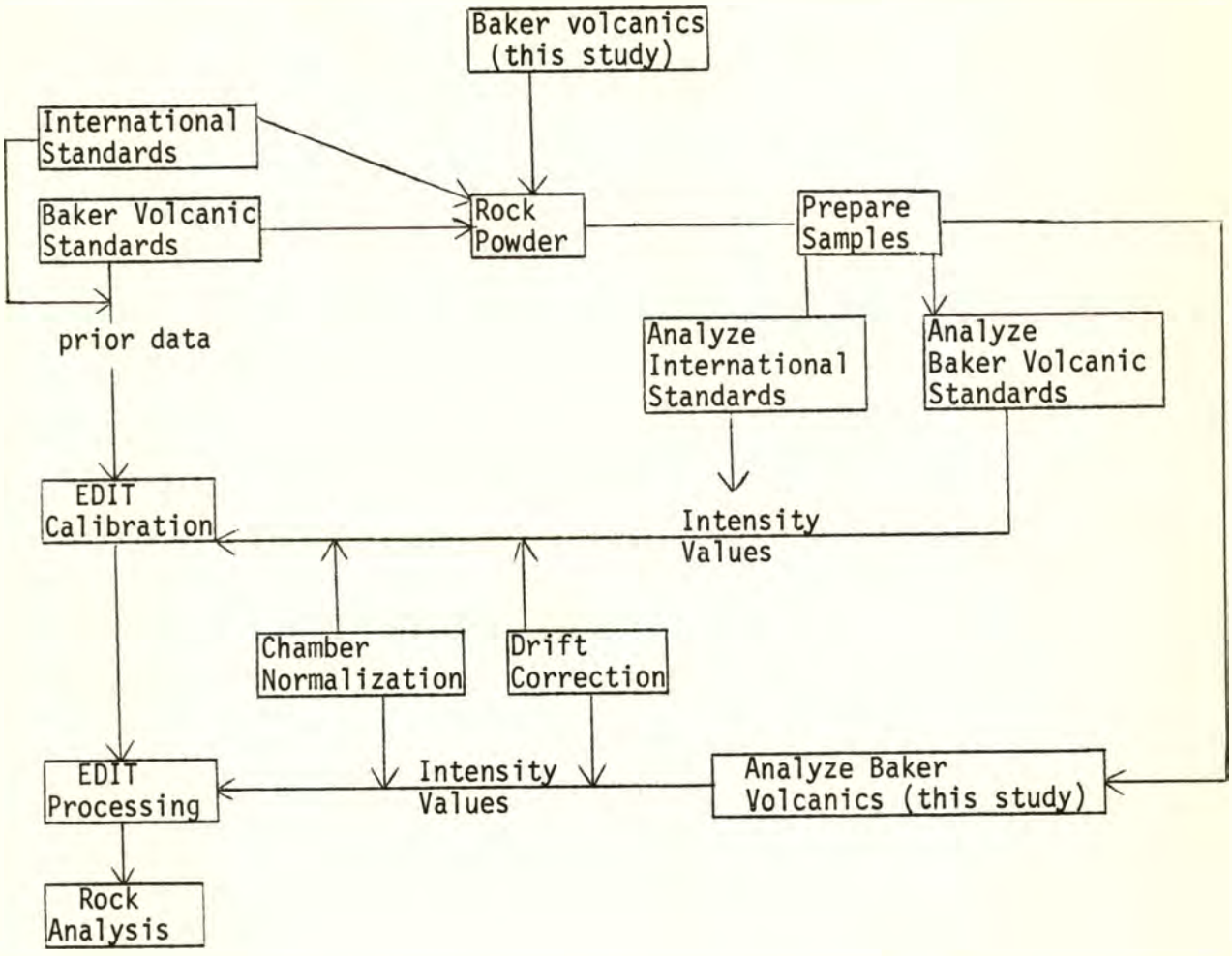
The second set of standards consisted of samples collected from the Baker volcanics by Stavert (1971). Samples are given in Table 8.

TABLE 8. Baker Volcanics Standards (Stavert, 1971)

Sample	Rock Type	Location
29-84	Basaltic olivine andesite	"Tarn Plateau" (Park Butte)
29-51	Basaltic andesite	Heliotrope Ridge
29-100	Basaltic andesite	Sulphur Creek
29-88	Basaltic andesite	Boulder Valley
29-98	Basaltic andesite	Coleman Glacier trough
29-81	Pyroxene andesite	Metcalfe Moraine
29-78	Pyroxene andesite	Easton Glacier trough
29-85	Pyroxene andesite	Boulder Valley
29-65	Andesite	The Portals (Mazama Glacier area)
29-59	Hornblende andesite	Ptarmigan Ridge dike

All samples prepared for analysis in this study were compared to calibration curves for each set of standards. Chemical compositions for the international standards are those recommended by Flanagan (1973), and the compositions used for the Baker volcanic standards are those determined by Stavert (1971). The procedure is shown schematically in Figure 27.

FIGURE 27. Procedure for Major Element Analysis of Silicate Rocks by the EDAX-EXAM-EDIT system (after Babcock and Mustoe, 1973).



Comparison of compositions of samples of the Baker volcanics was made by visual inspection. Comparison of samples selected from a wide range of silica composition using the two sets of standards is given in Table 9. Although the idea of using standards from the Baker volcanics is attractive, the concentration ranges for Stavert's analyses were more limited than the concentration ranges of the international standards. Although samples collected in this study are generally close to the

Table 9. Comparison of Selected EDAX Analyses Using Different Standards

	9/9K		8/5H		7/6D	
SAMPLE STANDARD	MAFIC	STAVERT	MAFIC	STAVERT	MAFIC	STAVERT
Na_2O	3.34	2.18	5.72	3.59	5.79	4.51
MgO	6.42	7.17	3.44	4.68	3.57	4.21
Al_2O_3	16.95	16.38	18.94	17.34	17.06	16.60
SiO_2	49.96	48.14	55.02	54.34	55.71	53.52
K_2O	0.42	0.60	0.96	0.94	1.27	1.34
CaO	8.78	9.66	8.83	9.71	6.98	7.68
TiO_2	1.00	1.85	1.14	0.88	1.29	1.27
Fe_2O_3[1]	11.35	14.25	7.31	9.30	8.31	10.19
MnO	0.16	0.11	0.11	0.06	0.15	0.06
TOTAL	98.38	100.34	101.47	100.84	100.13	99.38
qz	0.64	2.48	2.56[3]	4.23	2.5[4]	1.31
or	2.54	3.62	5.53	5.55	7.44	8.01
ab	30.73	20.00	45.81	32.21	51.58	40.97
an	30.76	33.86	22.60	28.41	16.68	21.34
mt	4.88	6.70	2.99	4.28	3.46	4.74
il	1.43	2.63	1.55	1.23	1.78	1.79
di	11.10	12.08	16.10	15.79	14.14	13.77
hy	17.92	18.64	2.85[4]	8.30	2.41	8.08
Norm Plag (% An)	50	63	33	47	24	34
D.I.	33.91	26.10	53.90	41.99	59.02	50.29
C.I.	35.33	40.05	23.49	29.60	24.29	28.38
FeO[2]	10.22	12.84	6.58	8.38	7.49	9.18

[1]Total iron oxide as Fe_2O_3

[2]Total iron oxide as FeO

[3]Percent Ne

[4]Percent Ol

Table 9 (contd.). Comparison of Selected EDAX Analyses Using Different Standards

	9/9P		9/17L		8/30C	
SAMPLE STANDARD	MAFIC	STAVERT	MAFIC	STAVERT	MAFIC	STAVERT
Na_2O	4.60	3.24	4.83	3.61	5.23	3.80
MgO	2.76	3.35	3.72	3.86	2.23	2.18
Al_2O_3	16.89	16.75	16.55	16.54	16.94	16.75
SiO_2	58.35	56.49	58.92	56.52	59.65	57.33
K_2O	1.40	1.51	1.58	1.65	1.54	1.73
CaO	6.26	6.88	6.33	6.96	5.39	5.93
TiO_2	0.75	0.52	0.91	0.69	0.78	0.45
Fe_2O_3[1]	6.36	7.95	6.85	8.36	5.98	7.43
MnO	0.10	0.04	0.11	0.05	0.11	0.04
TOTAL	97.47	96.73	99.80	98.24	97.85	95.64
qz	8.92	11.68	6.41	8.69	8.83	12.06
or	8.49	9.33	9.33	10.01	9.41	10.79
ab	42.38	30.43	43.33	33.27	46.84	36.04
an	21.86	27.93	18.80	24.69	19.29	24.87
mt	2.74	3.83	2.87	3.95	2.57	3.61
il	1.07	0.76	1.27	0.99	1.12	0.66
di	8.01	6.22	10.06	8.60	6.48	4.97
hy	6.54	9.82	7.94	9.81	5.46	7.00
Norm Plag	34	48	30	43	29	41
D.I.	59.79	51.44	59.07	51.97	65.08	58.89
C.I.	18.36	20.63	22.14	23.35	15.63	16.24
FeO[2]	5.73	7.16	6.17	7.53	5.38	6.69

[1]Total Fe as Fe_2O_3

[2]Total Fe as FeO

Table 9 (contd.). Comparison of Selected EDAX Analyses Using Different Standards

	9/16F		9/9C		7/23A	
SAMPLE STANDARD	MAFIC	STAVERT	MAFIC	STAVERT	MAFIC	STAVERT
Na_2O	4.79	3.58	4.43	3.32	4.91	3.95
MgO	2.48	2.88	2.66	3.04	2.34	2.61
Al_2O_3	16.41	16.55	16.21	16.58	15.84	16.41
SiO_2	60.37	58.05	59.84	58.18	61.62	59.71
K_2O	1.43	1.55	1.56	1.71	1.98	2.20
CaO	6.14	6.75	5.67	6.24	4.74	5.22
TiO_2	0.74	0.47	0.77	0.42	0.85	0.41
Fe_2O_3 [1]	6.11	7.51	5.87	7.36	5.74	7.08
MnO	0.10	0.04	0.01	0.04	0.11	0.04
TOTAL	98.57	97.38	97.10	96.89	98.13	97.63
qz	9.69	12.37	11.99	13.58	11.73	12.28
or	8.54	9.50	9.51	10.54	11.92	13.41
ab	42.65	33.36	41.04	31.11	44.92	36.58
an	20.17	25.44	20.37	26.40	15.63	21.20
mt	2.56	3.58	2.54	3.53	2.45	3.36
il	1.05	0.68	1.11	0.61	1.21	0.59
di	8.54	7.45	6.93	4.73	6.67	4.41
hy	6.78	7.61	6.52	9.50	5.47	8.17
Norm Plag (% An)	32	43	33	46	26	37
D.I.	60.88	55.23	62.54	55.23	71.06	62.27
C.I.	18.93	19.32	17.10	18.37	15.80	16.53
FeO [2]	5.50	6.77	5.29	6.63	5.17	6.38

[1] Total Fe as Fe_2O_3

[2] Total Fe as FeO

composition of Stavert's samples, the extreme concentrations for Na_2O, MgO, Al_2O_3, and MnO were notably higher and for total iron oxide, K_2O, TiO_2 and SiO_2 were notably lower than the extremes given by Stavert. These differences were noted regardless of which set of standards against which the rocks from this study were calibrated. Because of this, it is thought that calibration using the international standards would give the best results.

The predicted degree of uncertainty in a given analysis can be approximated by analyzing the reference standards as if they were unknowns. The results, listed in Table 10, indicate the best possible accuracies that can be expected for a given sample.

TABLE 10. Accuracy for Major Oxides in EDAX Analysis

OXIDE	ACCURACY
Na_2O	10%
MgO	10%
Al_2O_3	2%
SiO_2	1%
K_2O	1%
CaO	1%
TiO_2	10%
Total iron	9%
MnO	6%

In order to compare the results with those of another analyst, re-analyses were made of ten rocks, previously determined by Stavert (1971). The results of four of these cross-check analyses have been tabulated in Table 11. Concentrations are listed for the original analyses, and for EDAX-EXAM analyses compared to the international reference standards and to Baker volcanic standards (Stavert's own rocks). The

Table 11. Comparison of Selected Samples Analyzed by EDAX (this report) Vs. Original (Stavert, 1971).

SAMPLE METHOD	29-84 EDAX[m]	29-84 EDAX[s]	29-84 ORIGINAL[3]	29-100 EDAX[m]	29-100 EDAX[s]	29-100 ORIGINAL[3]
Na_2O	3.88	3.05	2.8	5.10	4.15	4.3
MgO	7.86	7.00	7.1	3.43	4.14	4.6
Al_2O_3	15.84	16.36	15.7	16.42	16.47	16.4
SiO_2	55.42	53.64	53.3	54.17	52.40	54.2
K_2O	0.88	0.85	0.9	1.15	1.26	1.3
CaO	9.30	10.22	10.3	6.79	7.47	7.7
TiO_2	0.92	0.95	0.9	1.30	1.36	1.3
Fe_2O_3[1]	7.97	9.92	10.2	8.60	10.71	11.0
MnO	0.14	0.06	0.06	0.14	0.07	0.07
TOTAL	102.21	102.05	100.9	97.10	98.03	100.9
qz	1.19	2.96	3.4	2.27	2.49	1.4
or	5.05	4.95	5.3	7.00	7.67	7.7
ab	33.82	26.99	25.0	47.16	38.39	38.6
an	22.53	28.03	27.5	19.07	23.28	21.6
wo	-	-	9.4	-	-	6.6
mt	3.56	4.50	4.4	4.07	5.08	4.1
il	1.24	1.30	1.3	1.86	1.95	1.8
di	17.81	17.56	-	12.50	11.93	-
hy	14.80	13.70	23.7	6.07	9.22	18.1
Norm Plag (%An)	40	51	52	29	38	36
D.I.	40.06	34.90	33.8	56.43	48.55	47.7
C.I.	37.41	37.06	29.3	24.50	28.18	24.0
FeO[2]	7.18	8.94	9.18	7.75	9.65	9.91

[1] Total Fe as Fe_2O_3

[2] Total Fe as FeO

[3] Si, total Fe, Ca, K, Ti by wave-length X-ray fluorescence; Al, Mg, Mn, Na by atomic absorption

[m] Mafic standards

[s] Stavert standards

- : not determined

Table 11 (contd.). Comparison of Selected Samples Analyzed by EDAX (this report) Vs. Original (Stavert, 1971).

SAMPLE METHOD	29-81 EDAX[m]	29-81 EDAX[s]	29-81 ORIGINAL[3]	29-59 EDAX[m]	29-59 EDAX[s]	29-59 ORIGINAL[3]
Na_2O	5.77	4.61	4.1	4.84	4.49	4.8
MgO	3.17	3.45	3.4	1.10	1.75	1.6
Al_2O_3	16.51	16.48	16.4	14.71	16.31	16.5
SiO_2	59.17	56.48	58.0	61.04	61.03	62.2
K_2O	1.69	1.76	1.8	2.32	2.68	2.7
CaO	6.08	6.69	6.6	3.64	4.01	4.1
TiO_2	0.94	0.75	1.0	0.73	0.19	0.8
Fe_2O_3[1]	7.95	8.51	8.3	4.81	6.34	6.0
MnO	0.12	0.05	0.05	0.10	0.02	0.04
TOTAL	100.50	98.78	99.6	93.29	96.82	98.7
qz	3.34	4.55	8.3	15.13	12.19	12.9
or	9.86	10.55	10.8	14.72	16.40	16.23
ab	51.16	42.00	37.2	46.68	41.76	43.8
an	13.98	19.36	21.3	12.42	17.03	15.7
wo	-	-	4.7	-	-	2.0
mt	3.20	3.97	3.5	2.38	3.02	3.5
il	1.29	1.06	1.4	1.09	0.27	1.1
di	12.65	11.46	-	5.58	2.87	-
hy	4.52	7.06	12.8	2.00	6.45	4.8
Norm Plag (%An)	21	32	36	21	29	26
D.I.	64.36	57.1	56.2	76.53	70.35	72.9
C.I.	21.66	23.55	17.7	11.05	12.61	9.4
FeO[2]	6.35	7.67	7.47	4.33	5.71	5.4

[1] Total Fe as Fe_2O_3

[2] Total Fe as FeO

[3] Si, total Fe, Ca, K, Ti by wave-length X-ray fluorescence; Al, Mg, Mn, Na by atomic absorption

[m] Mafic standards

[s] Stavert standards

- : not determined

agreement between my analyses and those of Stavert is fair, the principle differences being in the values for SiO_2, total iron oxide, MnO, Na_2O, and Al_2O_3. These differences are, in part, explained by the fact that Stavert made no corrections for Si-Al and Fe-Mn absorption-enhancement effects.

Oxidation State

Although initial oxidation state of iron in unaltered rock is very important in studies of petrogenesis, no attempt was made to determine oxidation state of iron. As analyzed total iron oxide is given as Fe_2O_3, and as portrayed in variation diagrams, total iron oxide is given as FeO.

The primary reason that no quantitative determination of Fe^{+2} and Fe^{+3} was made is because of known extreme variation of oxidation state of iron oxide within a single flow. It has been shown that while total iron oxide can vary by 9% from the mean for the flow, $Fe^{+2/+3}$ can vary by as much as 164% from the mean in 33 samples of otherwise comparable composition, depending upon the vertical position of the sample within the single flow (Watkins and Haggerty, 1967). Data from Mount Adams (Sheppard, 1967) show variation in $Fe^{+2/+3}$ by 25% from the mean in two samples from a single flow. Because of varying magnetite content in samples from different vertical positions within the same flow from the study area, it was assumed that large variation in oxidation state exists in the samples.

Still, Fe^{+2} and Fe^{+3} values are necessary to determine normative mineral percentages. These values were estimated from total Fe in the analyses of this study be determining the ratio of Fe_2O_3 to total Fe expressed as Fe_2O_3 (weight percents) for 2,015 analyses of rocks described

as calc-alkaline andesite (Chayes, 1969; Coombs, 1939; Nockolds, 1954; Stavert, 1971). The ratio obtained was 0.44, from which the approximate values for Fe^{+2} and Fe^{+3} can easily be obtained from total Fe. In addition, in 33 samples from one Icelandic lava, the average was 0.45 (Watkins and Haggerty, 1967). The average for 14 samples from Mount Baker was 0.44 (Coombs, 1939; Stavert, 1971), and the normative mineral percentages obtained from Stavert's rocks varied insignificantly whether the approximate ratio or the analyzed values for FeO and Fe_2O_3 were used. Therefore, the value of 0.44 can be used with more validity for the suite of Baker volcanic rocks than could be obtained by using separately determined, but likely misleading, values for Fe^{+2} and Fe^{+3}.

Major Element Stability During Alteration

Because the evidence available indicates that many of the major elements are susceptible to weathering, which increases their post-eruptive mobility (Pearce, 1976), only samples which were as visibly unweathered as possible were analyzed. One highly weathered sample was analyzed twice to determine the approximate effect of weathering upon EDAX-EXAM analysis. The total of the nine oxides was about 82%, with a portion of the remainder presumably being H_2O and CO_2. Low totals are typical of samples whose bulk mineralogy falls outside the range of that of the standards (George Mustoe, personal communication, 1977).

In a study of major element mobilities during subaerial weathering, Lisitsyna (1968) concluded that CaO, Na_2O, MgO, K_2O, and H_2O are very mobile, and total iron, Al_2O_3, and TiO_2 are immobile. Of primary significance is that the effects of subaerial weathering can result in misclassification of a suite of volcanic rocks into the incorrect tectonic setting and magma type (Pearce, 1976).

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GEOLOGIC MAP OF A PORTION OF THE SOUTH FLANK
OF MOUNT BAKER, WASHINGTON

EXPLANATION

Qa	Koma Kulshan Phase	Qa_1	Andesite and minor tephra of Sulphur Creek flow and Schriebers Meadow cinder cone.
		Qa_2	Andesite and minor tephra of Metcalfe Moraine, Railroad Grade, and Mazama Park.
Qvb	Black Buttes Phase		Volcanic breccia of Black Buttes Phase at Meadow Point.
Qba	Park Butte Phase		Basaltic olivine andesite and olivine basalt of Park Butte Phase. Units A,B, and C (Table 1) undifferentiated.
CPm	Chilliwack Group		Slate, phyllite, and metavolcanic rocks (undifferentiated).
pCm	Yellow Aster Complex		Meta-quartz diorite, hornblendite, and trondhjemitic gneiss.

Locations of analyzed samples indicated: • 9/16E

Contacts dashed where approximately located.

SCALE 1:24000

1 .5 0 1 KILOMETERS

CONTOUR INTERVAL 100 FEET

Deming
Creek
4000
RIVER
NOOKSACK
3000
Ridley
Creek
3500
4115
Divide
Bell Pass
BM 3964
4000
Creek
3000
South
Fork
T-4526
4915
5075
Meadow Point
Mazama Lake
Qvb
Mazama
Park
Qa2
Railroad
Grade
6155
6000
5500
T-5368
Qba
4500
4696
Baker Pass
BM 4962
CPm
Cathedral Crag
4846
4396
4339
pCm
5471
Park Butte
Qba
BM 4052
Pocket
pCm
5164
Glacier
Crag View
6511
Mercalfe
Moraine
Qa2
5000
4500
4839
Qa2
M 4487
4157
Schriebers Meadow
Qa1
BM 3263
T-3550
3500
CPm
4947
T-4055
4000
3000
372 D
500
8/14A
8/11A
8/12A
8/12B
8/6C
8/6B
8/6D
9/9G
9/7H
9/9F
9/7I
9/9E
9/9C
8/6B
8/6A
7/7A1
9/9B
8/5F
8/5E
8/5D
9/7J
8/5H
9/9A
8/5C
29-84
7/7B
9/7K
9/9A
8/5A
8/5B
9/9Q
9/9P
9/7M
9/7N
9/9R
9/7P
9/16C
9/16B
9/16A
7/6B
7/6C
7/6B
9/16B
9/17E
9/17F
9/17G
9/17D
9/17C
9/17H
9/17J
9/17I
9/3C
9/1D
9/3B
8/30F
8/30E
8/30D
8/30C
8/30A
8/30B
9/3A
9/2K
9/17B
9/17K
29-81
9/2J
9/3E
9/2I
9/17I
9/17A
9/17L
9/2H
9/3F
9/17M
9/2G
9/17N
9/2F
9/17O
9/2E
9/2D
9/2C
9/2B
9/2A